Modeling and Analysis of Cognitive Radio Ad Hoc Networks

Dissertation

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by M.Sc. Mohamed Abd rabou Ahmed Kalil
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vorgelegt der Fakultät für Informatik und Automatisierung
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Abstract

Wireless ad hoc networks are becoming more ubiquitous in terms of devices, application areas, etc. due to their low cost and minimal deployment effort. Since all these networks operate in the unlicensed band, the problems of congestion and spectrum scarcity have arisen. On the other hand, a recent study by Federal Communications Commission (FCC) has revealed that swathes of licensed bands, measured by 70%, are unutilized. This highlights that the actual problem is not the scarcity of spectrum but inefficient allocation policies and usage. Therefore, this dissertation is focused on improving spectrum utilization and efficiency to tackle the spectrum scarcity problem and support further wireless ad hoc networks.

This thesis proposes a new spectrum management concept called opportunistic spectrum access with backup channel (OSAB). The proposed concept provides secondary users (SUs) (e.g. ad hoc users) with the ability to adaptively and dynamically exploit channels from both licensed and unlicensed bands without interfering the legacy users of licensed bands, i.e. the so called primary users (PUs). Since existing radio systems offer very limited flexibility, cognitive radios (CR), which can sense and adapt to radio environments, are exploited to support such a dynamic concept. For the development of OSAB, the channels' characteristics from each band are taken into consideration. The main advantage of licensed channels is their availability in significant numbers, whereas, the main advantage of unlicensed channels is that all users have the same rights to channel access and thus no preemption occurs once a user obtains a channel. In addition, OSAB uses a backup channel (BC) to handle the appearance of PUs and thus facilitates SU communication. The proposed concept is extensively evaluated using a Markov chain model and compared to existing spectrum management approaches such as opportunistic spectrum access (OSA). The results indicate that in some cases, OSAB decreases the dropping probability and the expected number of spectrum handoffs for SUs compared to OSA by 60% and 17% respectively.

In order to apply OSAB practically, we develop a MAC protocol that reacts efficiently to sudden appearance of PUs. The new protocol is named opportunistic Spectrum access WITh backup CHannel (SWITCH) protocol. SWITCH is a decentralized, asynchronous, and contention-based MAC protocol. The BC's concept makes SWITCH extremely robust to the appearance of PUs. Each SU is equipped with two transceivers, one is tuned to a common control channel for the negotiation purpose with other SUs while the other is designed specifically to periodically sense and dynamically use the identified unused channels. To obtain the channel state accurately, we propose an efficient spectrum sensing strategy. This strategy is based on cooperative spectrum sensing among SUs. The performance of proposed protocol is evaluated through simulations. The results show that SWITCH accomplishes a remarkable 91.7% throughput gain over other CR-MAC protocols.

To conclude, the proposed contributions are a step forward towards efficient use of available radio resources and improve the spectrum capacity for wireless ad hoc networks.

Zusammenfassung

Eine Welt ohne drahtlose Ad-Hoc Netzwerke ist heute kaum noch vorstellbar. Auf Grund der geringen Kosten und des minimalen Installationsaufwands werden gegenwärtig immer mehr Geräte in immer mehr Anwendungsfeldern eingesetzt. Da die meisten dieser Netzwerke im lizenzfreien ISM-Band operieren, ist dieses heute stark ausgelastet und weist kaum noch freie Kapazitäten auf.

Aktuelle Studien der Federal Communication Commission (FCC) belegen allerdings, dass große Teile (bis zu 70%) der lizenzbehafteten Frequenzen ungenutzt sind. Dieser Umstand zeigt, dass das Problem weniger die generelle Knappheit an freien Frequenzen ist, sondern vielmehr in der ineffizienten Verteilung bzw. Nutzung der verfügbaren Resourcen zu suchen ist. Das Hauptaugenmerk der vorliegenden Dissertation liegt in der Verbesserung der Spektrumsauslastung, um dadurch die weitere Entwicklung von drahtlosen Ad-Hoc Netzwerken zu ermöglichen.

In dieser Arbeit wird ein neues Spektrum-Management-Konzept mit dem Namen *Opportunistic Spectrum Access with Backup channel (OSAB)* entwickelt und vorgestellt. Das hierbei zugrunde liegende Konzept gestattet *Secondary Users (SUs)* dynamisch und flexibel auf Frequenzen unlizenzierter als auch lizensierter Frequenzbänder zu zugreifen, wenn diese vom *Primary User (PU)* gerade nicht genutzt werden - es also keine Interferenzen geben kann.

Da der Zugriff auf das Frequenzspektrum heute existierender Systeme noch sehr unflexibel ist, soll dieser in Zukunft durch *Cognitive Radios (CR)* weit flexibler und dynamischer gestaltet werden können. Bei der Entstehung von OSAB wurden speziell die unterschiedlichen Eigenschaften verschiedener Frequenzbänder berücksichtigt. Der Hauptvorteil von lizenzbehafteten Bändern ist, dass diese in hoher Anzahl verfügbar sind. Der Hauptvorteil von lizenzfreien Frequenzen ergibt sich hingegen aus der Gleichstellung aller Nutzer. Sobald ein SU einmal einen Kanal belegt hat, kann er nicht mehr aus selbigem verdrängt werden. Kommuniziert OSAB in lizenzierten Bändern, so wird stets ein *BackupChannel (BC)* vorgehalten um auf das plötzliche Auftreten des PUs reagieren zu können. Das vorgeschlagene Konzept wurde in dieser Arbeit außerdem einer intensiven Analyse mittel Markov-Ketten unterzogen. Die dabei erzielten Ergebnisse zeigen, dass OSAB den Paketverlust und die erwartete Anzahl an Spektrum-Hand-Offs um 60% bzw. 17% reduzieren kann.

Um den Nutzen und die Vorteile von OSAB praktisch unter Beweis zu stellen, wurde in der vorliegenden Arbeit weiterhin das MAC-Protokoll SWITCH (opportunistic Spectrum access WITh backup CHannel) entwickelt. SWITCH ist ein dezentrales, asynchrones, verbindungsbasiertes MAC-Protokoll, welches durch das Backup-Channel-Konzept in der Lage ist, effektiv auf das plötzliche Eintreffen von PUs zu reagieren. Jeder SU ist dabei mit zwei Transceivern ausgestattet, wobei einer davon stets für die Kommunikation auf dem gemeinsam genutzten Kontroll-Kanal (Common Control Channel) verantwortlich ist. Der

zweite Transceiver ist so ausgelegt, dass dieser periodisch alle ungenutzten Kanäle absucht und dynamisch auf diese zugreifen kann. Um den Zustand eines Kanals (belegt/nicht belegt) korrekt erkennen zu können wird in dieser Arbeit eine einfache aber effektive Form des kooperativen Sensings genutzt. Die Performanz des Protokolls wurde mit Hilfe von Simulationen evaluiert. Die Ergebnisse zeigen, dass SWITCH im Vergleich zu anderen CR-MAC-Protokollen eine Verbesserung des Durchsatzes von bemerkenswerten 91,7% erzielen konnte.

Zusammenfassend kann gesagt werden, dass die vorgeschlagenen Beiträge einen Schritt hin zu einer effektiveren Nutzung der verfügbaren Funkressourcen und zur Erhöhung der Kapazität von drahtlosen Ad-Hoc Netzwerken darstellen.

Acknowledgments

Like many who come to Ilmenau from a bigger city, a different region, a larger university, a different climate, or a different culture, I was in shock when I arrived in Ilmenau in October of 2005. A feeling of regret stuck to me-had I made a horribly wrong decision when I chose this university in provincial Ilmenau to pursue the daunting task of earning a PhD? In my shock, I applied and was accepted to programs in Berlin, Hamburg and Wurzburg-cities that fit my ideas about "getting a PhD in Europe". But a call with my former Master's advisor, Prof. Hamed Nassar, back in Egypt made me reorder my priorities: he reminded me that the most important factor for my success wasn't the city I was at. It was the people I would work with and the environment they created. So I took some time to get to know these people and their working environment before making a decision and discovered my initial impression was completely wrong. The members of my group, the Integrated Communication Systems (ICS) group, were not only very active and successful in their research areas; they were also very supportive both academically and personally. I had never experienced such mutual cooperation and concern within a university group and I quickly realized that this research group was exactly where I wanted to pursue my PhD. I am very appreciative to many people in the ICS group for the completion of this dissertation.

Foremostly, I would like to thank my advisor Prof. Andreas Mitschele-Thiel, the head of the ICS group. Fortunately, Andreas was always watching me and at my side. He inspired me when I got stuck, encouraged me when my spirits were down, and challenged me when I was feeling sluggish. Also, I would like to give my special thanks to Prof. Jochen Seitz and Prof. Bruno Müller-Clostermann as members of my examination committee. Their advices greatly helped me to further improve the quality of this thesis.

My deep appreciation also goes to Dr.-Ing. Heinz- Dietrich Wuttke and Dr.-Ing. Karsten Henke for their warm friendship, and professional collaborations although their research areas are different from mine. My deep thanks go to my office mate throughout these last few years, Dipl.-Inf. Florian Liers. We always had something to talk about, sometimes about research, sometimes about our personal lives and sometimes about our collaboration on some of my papers. Also, I thank him for the precious time he took to review the first version of my thesis. I wish a continued success for him in the future.

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Abbreviations

ACK	.....	Acknowledgment
AP	.....	Access Point
ATIM	.....	Ad hoc Traffic Indication Map
BC	.....	Backup Channel
BSS	.....	Basic Service Set
CA	.....	Collision Avoidance
CCA	.....	Clear Channel Assessment
CCC	.....	Common Control Channel
CHMA	.....	Channel Hoping Multiple Access
CR	.....	Cognitive Radio
CSMA/CA	.....	Carrier Sense Multiple Access/Collision Avoidance
CTS	.....	Clear To Send
CU	.....	Classical User
CUL	.....	Current Usage List
CW	.....	Contention Window
DARPA	.....	Defense Advanced Research Projects Agency
DCA	.....	Dynamic Channel Allocation
DCA	.....	Distributed Channel Assignment
DCF	.....	Distributed Coordination Function
DECT	.....	Digital Enhanced Cordless Telecommunication
DFS	.....	Dynamic Frequency Selection
DIFS	.....	Distributed Coordination Function Interframe Space
DSA	.....	Dynamic Spectrum Access
EIFS	.....	Extended Interframe Space
ESS	.....	Extended Service Set
FCC	.....	Federal Communications Commission
FCL	.....	Free Channel List
FCT	.....	Free Channel Table
IEEE	.....	Institute of Electrical and Electronics Engineers
IBSS	.....	Independent Basic Service Set
IFS	.....	Interframe Space
ISM	.....	Industrial, Scientific and Medical
LC	.....	Licensed Channel
LLC	.....	Logical Link Control
MAC	.....	Medium Access Control
MACA	.....	Multiple Access with Collision Avoidance
MACAW	.....	MACA Wireless
McMAC	.....	Multi-channel MAC
MSC	.....	Message Sequence Chart
NAV	.....	Network Allocation Vector

NCL	.....	Neighbor Channel List
NTR	.....	Notification To Reserve
OSA	.....	Opportunistic Spectrum Access
OSAB	.....	Opportunistic Spectrum Access with Backup channels
OSI	.....	Open System Interconnection
PCF	.....	Point Coordination Function
PCS	.....	Physical Carrier Sensing
PDC	.....	Proposed Data Channel
PIFS	.....	Point Coordination Function Interframe Space
PU	.....	Primary User
QoS	.....	Quality of Service
RA	.....	Receiver Address
RES	.....	Reservation
RTS	.....	Request To Send
SCC	.....	Standard Coordination Committee
SDC	.....	Selected Data Channel
SDR	.....	Software Defined Radio
SIFS	.....	Short Interframe Space
SSCH	.....	Slotted Seeded Channel Hopping
SU	.....	Secondary User
SWITCH	.....	opportunistic Spectrum access WITh backup CHannel
TA	.....	Transmitter Address
TTM	.....	Time To Mask
UC	.....	Unlicensed channels
UML	.....	Unified Modeling Language
UMTS	.....	Universal Mobile Telecommunication System
UWB	.....	Ultra-Wideband
U-NII	.....	Unlicensed National Information Infrastructure
VCS	.....	Virtual Carrier Sensing
WLANs	.....	Wireless Local Area Networks
XG	.....	neXt Generation

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Wireless ad hoc networks gain importance with the rapid development in wireless communication technologies. They are an important part of the envisioned future ubiquitous communication since they do not require infrastructure support and can be deployed rapidly with minimal effort and at low cost [1][2].

Nowadays, the majority of wireless ad hoc networks are operating in the 900 MHz, the 2.4 GHz and the 5 GHz unlicensed Industrial, Scientific and Medical (ISM) bands [3]. Furthermore, they are mainly based on IEEE 802 standards. Within the IEEE 802.11 a/b/g frequency bands, the number of available channels is limited. The bands, used by 802.11b/g and 802.11a, provide 3 and 12 non-overlapping frequency channels, respectively. With the growing proliferation of wireless devices, these bands are increasingly getting congested. In contrast, there are several licensed bands, such as in the 400-700 MHz range, which are only partly used. The Federal Communications Commission (FCC) initiated a study of this issue in November 2002 [4]. The study has revealed that swathes of the spectrum, measured by 70%, are unutilized.

The inefficiency of spectrum utilization has attracted a flurry of exciting activities in academia and industry in searching for new spectrum management concepts to access and use the spectrum dynamically. One of these concepts, called opportunistic spectrum access (OSA), has been investigated by the DARPA Next

Generation (XG) program as a spectrum management concept which gives the secondary users (SUs) (ad hoc devices) the opportunity to access unused parts of the licensed spectra [5]. OSA has been identified as a promising solution to alleviate the apparent spectrum scarcity problem in the unlicensed ISM bands. Consequently, the cognitive radio (CR) technology [6][7] is developed to realize the OSA concept. The basic idea of CR technology is that the SUs utilize unused spectrum in the licensed band without interference with the primary users (PUs). Once a PU appears in a channel occupied by an SU, the SU should vacate the channel and determine a new channel for continuing its transmission.

1.1 Motivation

Despite the advantages of OSA and CR, such as increasing the spectrum capacity of ad hoc networks, some challenges have not been addressed so far:

First, although devices with CR capabilities are designed to operate over channels from both licensed and unlicensed bands [8], most of the research is focusing on the behaviour of the SU over channels from the licensed band only, supposing that the other channels from the unlicensed band are always saturated and therefore the impact of these channels is neglected. The possibility, that such channels might be free, is not considered when the SUs coordinate access to the available spectrum. This leads to an inefficient utilization of the spectrum and wastes network resources.

Second, although the average spectrum usage will be increased when applying OSA and CR, the effect of the sudden appearance of PUs is less explored and research is still in its infancy. We believe that consecutive spectrum handoffs by SUs among different unoccupied spectra have a negative effect in terms of delay, and thus an effective solution should be developed.

Third, most of the existing CR-MAC protocols are not coping efficiently with the appearance of PUs. In these protocols, an SU should establish a new agreement with its receiver every time the PU appears which maximizes the control message overhead in the network and thus increases the SU delay.

The aforementioned problems motivated us to: 1) develop a new spectrum management concept that manages and organizes the access to the available spectrum efficiently regardless of the fact that it is licensed or unlicensed. The new concept should overcome the problems of OSA such as the sudden appearance of PUs, and 2) propose a new MAC protocol to exploit the advantage of the expected large number of channels (unlicensed and licensed channels). The most important feature of this protocol is fast link maintenance with minimum control overhead in the case of PUs appearance.

1.2 Contributions

The thesis provides two contributions. The first contribution proposes a future spectrum management concept to overcome the OSA challenges. In the second contribution, we propose a MAC protocol to implement the proposed concept.

1.2.1 Contribution 1: Opportunistic spectrum access with backup channel (OSAB)

The majority of the existing approaches for spectrum management, proposed for CR networks such as [9][10], are based on the OSA concept which allows every SU to use a particular pool of channels from a licensed band opportunistically. Furthermore, if a PU shows up in one of the channels occupied by an SU, the SU should vacate that channel and perform a spectrum handoff to a free one immediately. These approaches neglect the existence of other channels from the unlicensed band when SUs perform a spectrum handoff. Moreover, these approaches also assume that the network itself is centrally managed. Thus, they cannot be applied to ad hoc networks which lack the centralized entity.

We believe that a better approach is to allow SUs to access channels from both bands, i.e. licensed and unlicensed, for efficient utilization of the available spectrum. To achieve our goal, we develop a new spectrum management concept named OSAB. OSAB is a spectrum management concept for CR ad hoc networks that organizes the access to the available spectrum resources efficiently regardless of the fact that it is licensed or unlicensed. Furthermore, OSAB overcomes OSA challenges such as the way the SU copes with the appearance of PUs. The main assumptions for the proposed concept can be listed as follow:

- There are two types of channels: licensed channels (LCs) and unlicensed channels (UCs). The LCs are shared between PUs and SUs with high priority for the PUs to access the channels. The UCs are shared between SUs and classical users (CUs) (i.e. users without cognitive capabilities) with equal priority to access the channels

- We assume that SUs initially use the lowest utilized channel from the LCs as operating channel. By operating channels, we mean channels used for data transmission.

- In the case of PU appearance, OSAB assumes a backup channel (BC) to reconstruct and maintain the SU communication. Each SU selects a BC prior to its actual data transmission. The BC is a channel selected from LCs or UCs pool according to the spectrum availability with high priority given to the UCs since they are free from PUs. If all UCs are occupied, the lowest utilized channel from the LCs is selected as a BC. This simple scheduling scheme for the selection of the BC will lead to lower packet dropping probabilities. Furthermore, the BC's conception prevents the SUs from periodic sensing in order to search for a new channel. Thus, the coordination overhead, involved in case of switching to a new channel, is minimized.

From the aforementioned assumptions, the more efficient usage of the available spectrum (licensed or unlicensed) and the BC's conception are distinguishing the OSAB concept from OSA.

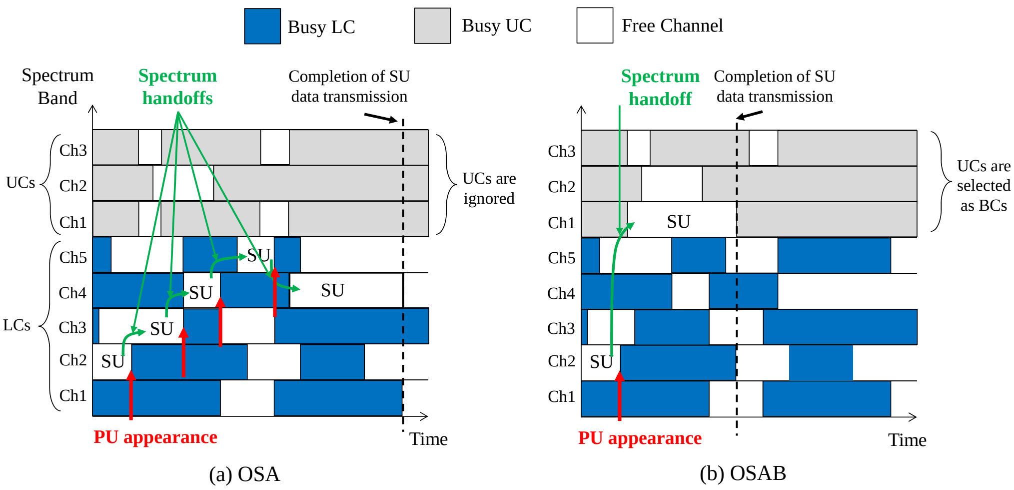


Figure 1.1: Spectrum access strategies

Figure 1.1 shows a simple example of spectrum access for both OSA and OSAB. This example describes only one case, different cases will be described later. In this figure, there are 5 LCs and 3 UCs. We assume that the data transmission may continue over more than one channel due to PUs activities. We assume that the SU operates in a highly dynamic environment where the availability of each channel varies over time.

As shown in Figure 1.1-(a), an SU starts its transmission on channel 2 from the LCs. Due to the sudden appearance of the PU, the SU performs a spectrum handoff to channel 3 to continue its transmission. This process repeats until the SU has finished its data transmission. As seen from the figure, OSA neglects the existence of the UCs when it performs a spectrum handoff. Thus, the number of spectrum handoffs is increased which increases the time needed to transmit the data.

As depicted in Figure 1.1-(b), an SU start its transmission on channel 2 from the LCs. Since channel 1 from the UCs is free, the SU utilizes this channel in the case of sudden appearance of a PU. In such a case, the SU will not perform any more spectrum handoff since the UCs are free from PUs. OSAB reduces the number of spectrum handoffs which reduces the time needed to transmit the data.

Due to the dynamics of OSAB, the Markov chain process is selected as performance evaluation tool since it provides very flexible, powerful, and efficient means for the description and analysis of OSAB network. Detailed analytical models for both OSA and OSAB are developed to evaluate and compare both concepts. The results indicate that OSAB decreases the blocking probability and the dropping probability for SUs compared to OSA up to 44% and 61.79%, respectively.

Different parts of this work appear in the following papers:

M. Kalil, H. Al-Mahdi and A. Mitschele-Thiel "Analysis of Opportunistic Spectrum Access in Cognitive Radio Ad Hoc Networks" in Proc. 16th International Conference on Analytical and Stochastic Modelling Techniques and Applications (ASMTA'09), 2009

M. Kalil, F. Liers, T. Volkert and A. Mitschele-Thiel "A Novel Opportunistic Spectrum Sharing Scheme for Cognitive Radio Ad Hoc Networks" Electronic Communications of the EASST, Vol. 17, pp. 676–678, 2009

H. Al-Mahdi, M. Kalil, F. Liers and A. Mitschele-Thiel "Increasing spectrum capacity for ad hoc networks using cognitive radios: an analytical model" IEEE Communications Letters, Vol. 13, pp. 676–678, 2009

Furthermore, we extend the aforementioned analytical model to calculate more performance metrics such as the expected number of spectrum handoffs, and effective transmission time. Interestingly, the results show that OSAB decreases the expected number of spectrum handoffs and the effective transmission time compared to OSA by up to 39.88% and 26.5%, repectively. This part appears in the following paper:

M. Kalil, H. Al-Mahdi and A. Mitschele-Thiel "Spectrum Handoff Reduction for Cognitive Radio Ad Hoc Networks " Proc. Workshop on Cognitive Communications (WUN COGCOM 2010) in conjunction with The Seventh International Symposium on Wireless Communication Systems (ISWCS'10), York, United Kingdom, 19-22 September, 2010.

1.2.2 Contribution 2: SWITCH: an opportunistic Spectrum Access WITh backup CHannel MAC Protocol

The OSAB concept is a spectrum management concept that uses the available spectrum more efficiently. However, OSAB is an abstract concept, some open issues still exist such as: *How do transmitters and receivers coordinate access to the available spectrum? How does the SU cope with the sudden appearance of the PU?* Thus, a detailed MAC protocol is needed to answer the aforementioned questions.

This was a motivation for us to develop a new MAC protocol called opportunistic Spectrum access WITh backup CHannel (SWITCH) protocol. SWITCH is proposed to implement the OSAB concept.

In order to handle the first issue mentioned above, SWITCH extends the IEEE 802.11 MAC protocol to mimic the dynamics of OSAB. Some modifications are proposed to control messages to make the coordination process between transmitter and receiver more efficient. For example, extra fields are added to control messages to exchange both the proposed data channel and the BC during the negotiation process between the transmitter and receiver.

For the second issue, SWITCH uses the BC's conception presented by OSAB. The BC is negotiated between the transmitter and receiver prior to the actual data transmission. Thus, when a PU appears, both transmitter and receiver switch to the BC without additional control messages which lead to minimizing the control overhead required to find a new channel in the case of PU's appearance. Furthermore, all nodes in the transmission range of both nodes are informed about such a switch and therefore a collision will be reduced.

The SWITCH protocol is a flexible MAC protocol to operate over the LCs and the UCs. This feature gives the proposed protocol an advantage over other CR-MAC protocols. In the proposed protocol, the control packets will be sent in a separate control channel. It is assumed that the control channel is chosen from the LCs by FCC. The purpose of the control channel is to resolve the contention on data channels and to assign data channels to each node. The other LCs and UCs will be left for data transmission and acknowledgments. The data channels will be sorted according to the activity of the PUs in each channel observed by SUs. In addition, each node is assumed to be equipped with two transceivers. The first transceiver is devoted to operating over the control channel. The SUs use this transceiver to obtain the information of the unused LCs and UCs, and to negotiate with the other SUs. The second transceiver consists of a Software Defined Radio (SDR) module. This module can tune to any one of the available channels, LCs and UCs, to sense for the unused spectrum and moreover receive/transmit the SUs' packets. Moreover, we assume an efficient spectrum sensing strategy for better utilization of the available spectrum. This strategy is based on cooperative spectrum sensing where the sensing results (i.e. LCs and UCs) are combined from SUs in the network. In this way, the chance of missing signals from PUs, CUs, and other SUs can be reduced which leads to a better utilization of the available radio resources.

The performance of the proposed protocol is evaluated using simulation. The results show that SWITCH increases the throughput up to 91.7% compared to other CR-MAC protocols.

To summarize, in this dissertation

- we introduce a new spectrum management concept named OSAB. OSAB was designed to overcome some of the problems of OSA such as the way the

SU copes with the sudden appearance of PUs. Furthermore, we develop a Markov chain model to evaluate OSAB. The results show significant improvement compared to OSA in terms of dropping probability, channels utilization, the expected number of spectrum handoffs and link maintenance probability

- we also develop a new CR-MAC protocol called SWITCH to implement OSAB. The proposed protocol is evaluated using simulation.

1.3 Structure of the dissertation

This dissertation has five chapters, as shown in Figure 1.2, and is organized as follows:

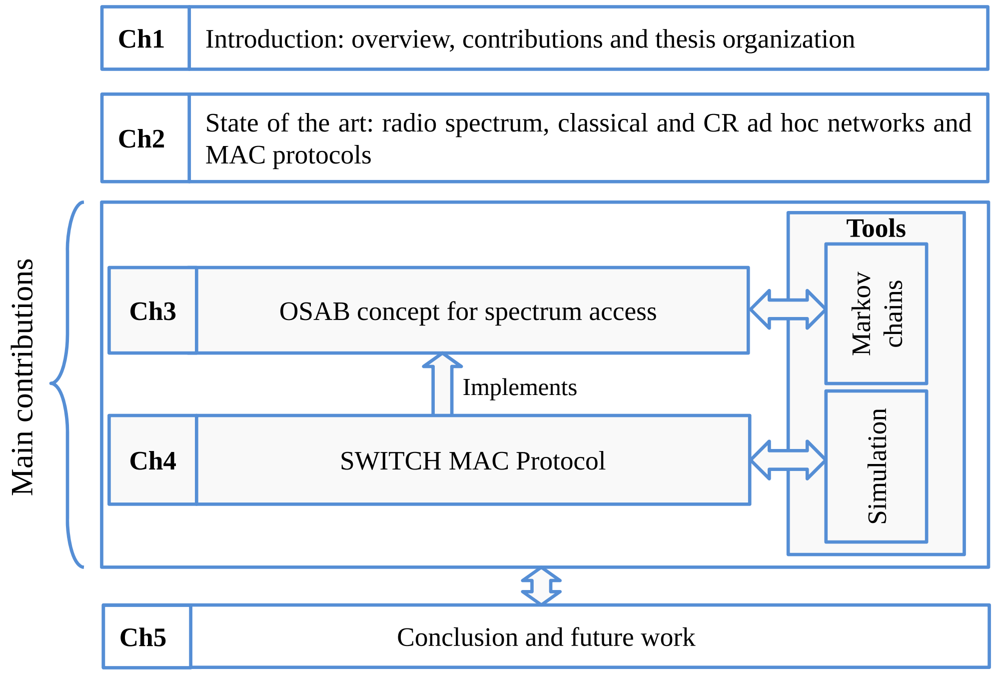


Figure 1.2: Structure of the dissertation

In **Chapter 2**, we present an overview of the radio spectrum and state of the art for ad hoc networks. A detailed overview of the IEEE 802.11 standard is given since it is used by most of wireless devices nowadays. Furthermore, the OSA concept and the CR technology are presented as powerful candidates for solving the spectrum scarcity problem for classical ad hoc networks. The chapter gives also an overview about the research challenges that will be handled through this thesis.

In **Chapter 3**, the new spectrum management concept, OSAB, that organize and manage the access to the available spectrum efficiently to overcome some of the OSA challenges, is introduced. This chapter corresponds to Contribution 1. A theoretical formulation, based on a Markov chain process, is developed to evaluate comprehensively the performance of the proposed concept and to compare it with the classical OSA.

In **Chapter 4**, a new CR-MAC protocol called SWITCH is proposed to implement the new concept developed in Chapter 3. The chapter presents design features and main assumptions of the proposed protocol. Moreover, an efficient cooperative spectrum sensing strategy is proposed. This chapter corresponds to Contribution 2. The proposed protocol is extensively evaluated using simulation. In addition, some of the results, obtained from Chapter 3, are also validated using the developed simulator.

In **Chapter 5**, we summarize our contributions and draw some conclusions. Furthermore, we highlight possible future research directions for open problems in the thesis.

Chapter 2

Radio spectrum and ad hoc networks: Overview

In this chapter, an overview of wireless ad hoc networks and the spectrum availability for such networks in both the present and the future, is given. Furthermore, the main challenges for such networks are presented.

2.1 Introduction

The unlicensed spectrum bands are being increasingly used by different services and technologies such as wireless mesh networks, wireless sensor networks and wireless ad hoc networks for a variety of military, environmental monitoring and commercial applications. This has led to the problem of spectrum scarcity in the unlicensed band. At the same time, the frequencies reserved for licensed use, such as television broadcast, are not always occupied, leading to inefficient utilization of the resource. Modern spectrum management concepts such as Dynamic Spectrum Access (DSA) and OSA will give ad hoc devices the opportunity to access the unused spectrum from the licensed band without interference with the PUs [11][12]. Thus, solving the spectrum scarcity in the unlicensed bands and furthermore solving the inefficient spectrum usage in the licensed bands.

This chapter presents an overview about the spectrum availability for wireless ad hoc networks today and how ad hoc devices coordinate to access this spectrum. Due to its popularity, a deep overview about IEEE 802.11 MAC is presented. In addition, the chapter presents an overview about future spectrum management concepts, such as DSA and OSA, which are promising solutions for spectrum scarcity in the todays' ad hoc networks. Finally, the chapter presents the main research challenges for such future spectrum management concepts.

2.2 Wireless ad hoc networks

A wireless ad hoc network is a decentralized and self-organized wireless network. It consists of wireless devices (nodes) such as laptops and PDAs forming a temporary network without the aid of any centralized entity such as base stations [1] [2]. Each node is a host and router at the same time. The node is a host, when it sends data to another node and a router when it forwards data to other nodes. The decision which node has to forward data is made dynamically based on the network connectivity. This is in contrast to wired networks in which routers perform the task of routing. It is also in contrast to infrastructure-based wireless networks, in which an access point manages communication among other nodes. In 1970, the notion of ad hoc wireless networking was firstly established by the Defense Advanced Research Projects Agency (DARPA) [2]. The term "ad hoc" implies that this network is a network established for a special and unprepared service for a certain purpose and for a limited period of time e.g., to establish a video conference among two teams engaged in a rescue effort.

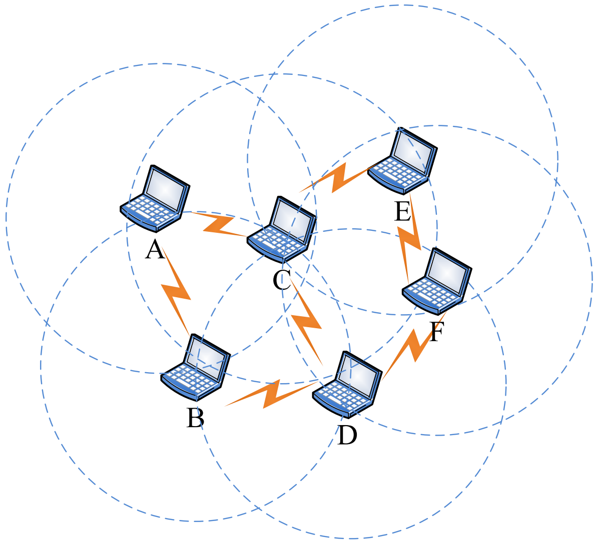


Figure 2.1: Classical ad hoc networks

Figure 2.1 shows an example of an ad hoc network. The figure illustrates that the laptops communicate with each other without centralized entity such as base stations. Several unique characteristics distinguish wireless ad hoc networks from their wired counterparts. These characteristics can be listed as follows [13]:

- Mobility: the fact that nodes can be rapidly repositioned and/or move is one of the characteristics of ad hoc networks. Rapid deployment in areas with no infrastructure often implies that the users must explore an area and perhaps form teams or swarms that in turn coordinate among themselves to execute a mission. Different mobility models can be used such as random mobility, group mobility, etc. The mobility model can have a major impact on the selection of a routing scheme and can thus influence performance.

- Multihopping: a multihop network is a network where the path from source to destination traverses through several other nodes. Ad hoc networks often exhibit multiple hops for obstacle negotiation, spectrum reuse, extend the range of communication and energy conservation.

- Self-organization: the ad hoc network must autonomously determine its own configuration parameters including: addressing, routing, clustering, position identification, power control, etc.

- Energy conservation: most ad hoc nodes (e.g., laptops, PDAs, sensors, etc.) have limited power supply and no capability to generate their own power (e.g., solar panels). Energy efficient protocol design (e.g., MAC, routing, resource discovery, etc) is critical for longevity of the mission.

2.3 Radio spectrum

Radio spectrum can be defined as a part of the electromagnetic spectrum which is used for transmitting voice, video and data. It uses frequencies from 3 kHz to 300 GHz. Radio spectrum is organized by national and international institutions that are usually referred to as "regulators" [12]. The regulation of radio spectrum can be differentiated into three models [4] [12]: Licensed spectrum for exclusive usage, licensed spectrum for shared usage, and unlicensed spectrum. In the next sections, we give an overview of these models.

2.3.1 Licensed spectrum for exclusive usage

In this model, each licensee has exclusive and transferable rights to the use of specified spectrum within a defined geographic area, with flexible use rights that are governed primarily by technical rules to protect spectrum users against interference. Frequency bands sold for use in the Universal Mobile Telecommunication System (UMTS) in Europe are an example of an exclusive usage right for a licensed spectrum.

2.3.2 Licensed spectrum for shared usage

This model is called also "command-and-control" model. This model is the legacy model by which an administration licenses spectrum to users under specific conditions. Changing uses of spectrum is deliberative process that involves study and opportunities for public comment. An example of this approach is the spectrum assigned to Digital Enhanced Cordless Telecommunication (DECT).

2.3.3 Unlicensed bands

A small part of the radio spectrum is allocated to the unlicensed band. The access to unlicensed band is open. A large number of users are sharing the same unlicensed spectrum. Spectrum utilization is permitted to all devices with equal priorities that fulfil certain technical rules in order to avoid interference. The most famous unlicensed frequency bands are: The ISM bands [14] and the Unlicensed National Information Infrastructure (U-NII) band [15]. Although a small fraction of the radio spectrum is assigned to the unlicensed bands, a wide variety of new wireless standards, technologies, and services, among them the popular IEEE 802.11 are using it. Therefore, this portion of spectrum is getting congested and overcrowded. As a result, a new problem appears in the unlicensed band. This problem is called the spectrum scarcity problem. This problem happens as a result the way spectrum is regulated not due to limited radio resources. Thus the traditional regulation of spectrum requires a fundamental rethinking in order to avoid waste of spectrum and, hopefully, to overcome the spectrum scarcity problem. One approach to solving this paradox is allowing the unlicensed users i.e. SUs to access dynamically and opportunistically the unutilized parts from the licensed spectrum with minimum interference with the legacy users i.e. PUs.

In this thesis, we focus on increasing the spectrum capacity of wireless ad hoc networks to overcome problems such as spectrum scarcity problem. We reach this goal by exploiting and enhancing futurist spectrum management approaches such as DSA and OSA. In next sections, we give an overview about the current state of wireless ad hoc networks: i.e. *what is the most popular standard for such networks?*, *How do they coordinate the access to the available spectrum?*...etc. In addition, we summarize the future vision for such networks: i.e. new spectrum management approaches, technologies and challenges.

2.4 Spectrum availability for ad hoc networks: the present

Nowadays, wireless ad hoc networks are mainly operating on the ISM bands. There are two main unlicensed radio bands used for IEEE 802.11 networks: The 2.4 GHz band and the wider 5 GHz bands. Although, the 2.4 GHz is very narrow and only supports 3 non-overlapping channels, it hosts unfortunately the vast majority of wireless devices because of backward compatibility issues. The wider 5 GHz bands which mostly go unused have an 8-channel block of spectrum in the 5.3 GHz range and a 4-channel block in the 5.8 GHz range for a total of 12 non-overlapping channels.

The spectrum allocation allows IEEE 802.11 devices to operate within a band, and the selection of a particular frequency is accomplished through protocols and etiquettes. The next section, will give an overview about IEEE 802.11.

2.4.1 IEEE 802.11 in the unlicensed band

Wireless networks operating in the unlicensed band (e.g., ISM band), are typically not designed to exchange information between dissimilar radio networks. 802.11 networks have to share, for instance, the unlicensed band with other radio access technologies such as Bluetooth. Thus, the operation in unlicensed spectrum requires basic coexistence capabilities.

802.11 networks have an hierarchical architecture, as illustrated in Figure 2.2. Its basic element is the Basic Service Set (BSS), which is a group of stations controlled by a so-called coordination function. The coordination function manages the access to the wireless medium and supports two modes:

- Distributed Coordination Function (DCF) mode (for ad hoc networks) and
- Point Coordination Function (PCF) mode (for infrastructure-based networks).

An Independent Basic Service Set (IBSS) is the simplest 802.11 network type. It is a network consisting at least of two stations, where each station operates

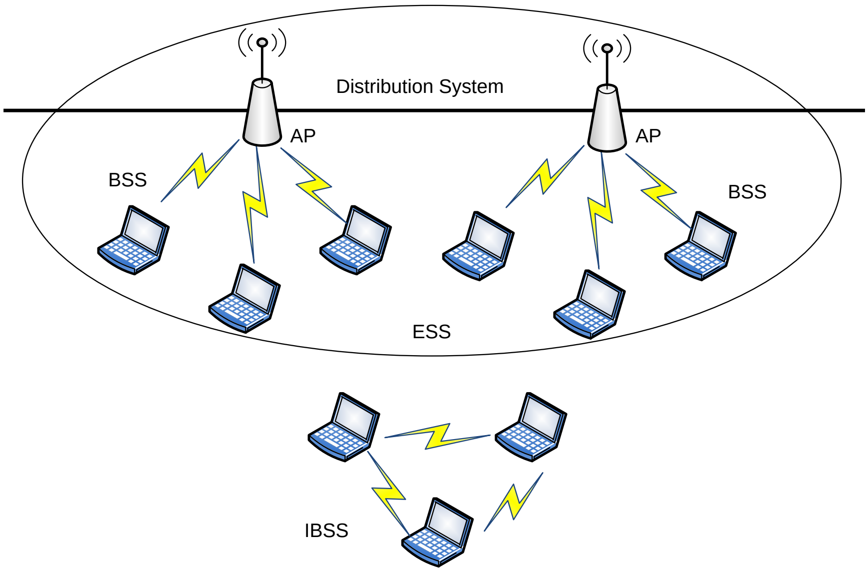


Figure 2.2: IEEE 802.11 basic architecture

with exactly the same protocol. No station has priority over another, and the responsibility for coordinating medium access is distributed between all stations. An infrastructure-based BSS includes one station that has access to the wired network and which is therefore referred to as the Access Point (AP). A BSS may also be part of a larger network, the so-called Extended Service Set (ESS). This ESS consists of one or more BSSs connected over a distribution system, for instance 802.3 Ethernet.

The 802.11 standard focuses on the layers one and two of the Open System Interconnection (OSI) reference model which are Data Link Control layer (i.e., OSI layer-2) and Physical layer (PHY) (OSI layer-1). The 802.11 reference model divides the Data Link layer into Logical Link Control (LLC) and MAC sublayers. Further details about 802.11 layers can be found in [16]. Our focus in this thesis is the MAC layer and how nodes coordinate access to the available spectrum. The next section gives an overview about the main access techniques for wireless ad hoc networks especially IEEE 802.11 MAC.

2.4.2 Medium access control

All nodes in a wireless ad hoc network use the same physical channels and the number of channels is limited. Therefore, MAC protocols play an important role in coordinating access to the available channels. The number of available channels affects greatly the data collision probability. Obviously, if all nodes operate in one channel, the probability of data collision increases and therefore the network throughput decreases. In contrast, increasing the number of channels will increase the throughput for the whole network.

In wireless ad hoc networks, spectrum is a scarce and precious resource, so that the spectrum should be used efficiently in order to offer as much bandwidth as possible for running applications. Therefore, the design of MAC protocols is a subject of active research in both academia and industry. The primary goal of MAC is to coordinate the channel access among multiple nodes to achieve a high channel utilization. In other words, the coordination of channel access should minimize data collisions and maximize spatial reuse at the same time.

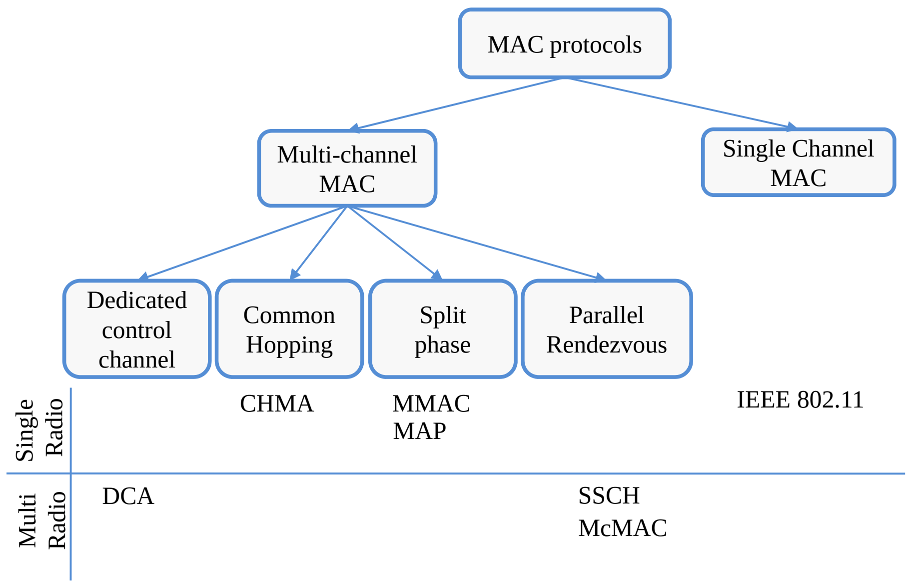


Figure 2.3: Classification of MAC protocols for wireless ad hoc networks

From Figure 2.3, the MAC protocols for wireless ad hoc networks can be classified into two main categories according to the number of channels: single channel protocols and multichannel protocols [17]. In single channel protocols, all nodes utilize a single channel for communications. In multichannel protocols, there is more than one channel and every node can utilize any one of those channels for communications. Single channel MAC protocols suffer from several problems compared to multichannel ones. For example, when a node operates in a single channel environment, other nodes in the transmission range of this node are prohibited from transmitting any packets. Furthermore, collisions may occur when the network get saturated. In addition, the throughput will be decreased as a result of different problems such as the hidden node problem, the exposed node problem and the masked node problem [18]. By using multiple channels, the effects of the aforementioned problems can be reduced, since different devices can transmit in parallel on distinct channels. Therefore, the network throughput will increase.

2.4.3 Single channel MAC protocols

With single channel MAC protocols, all the nodes in the network share the medium for all their control and data transmissions. Collisions are an inherent attribute of such protocols. If two stations transmit simultaneously, they will both fail, and therefore a backoff mechanism is required by both stations.

The first proposed single channel protocol was Carrier Sense Multiple Access (CSMA) [19]. CSMA does not address collisions on the channel and no solution for the hidden node problem was presented. Details about CSMA are given in Section 2.4.3.1. Multiple Access with Collision Avoidance (MACA) [20] and MACA Wireless (MACAW) [21] has been proposed as an improvement over CSMA to eliminate the hidden node problem. Both protocols use Request To Send (RTS)/Clear To Send (CTS) messages to handle the hidden node problem. IEEE 802.11 MAC [16] is one of the most popular MAC protocols for wireless ad hoc networks. Many of the MAC protocols discussed in this thesis are based on it.

2.4.3.1 IEEE 802.11 MAC

IEEE 802.11 MAC is based on CSMA/Collision Avoidance (CA), which can be seen as a combination of the CSMA [19] and MACA [20] protocols. The scheme, named DCF, is used to coordinate access among different ad hoc devices. In the following, an overview about the IEEE 802.11 DCF scheme is presented, e.g., channel sensing, timing, collision avoidance and channels reservation. More details about these methods can be found in [16].

Channel sensing

802.11 uses two sensing mechanisms: Physical Carrier Sensing (PCS) and Virtual Carrier Sensing (VCS). For the PCS, a single fixed power threshold (-82 dBm according to 802.11) is used by each node to sense the media. If the signal with power larger than the aforementioned threshold is detected by a node, the channel is assumed to be busy and no transmission is available in this channel. Otherwise, the channel is assumed to be idle. For the VCS, a timer called Network Allocation Vector (NAV) is used. This timer decreases irrespective of the status of the medium, which can be busy or idle. The NAV is set when a frame is received that includes a duration field defining how long the following frame exchange may take. The node is not allowed to transmit as long as the NAV is set or the PCS has sensed the radio channel as being busy.

Timing

IEEE 802.11 defines four different Interframe Space (IFS), as shown in Figure 2.4, with different priority levels for medium access: Short Interframe Space (SIFS),

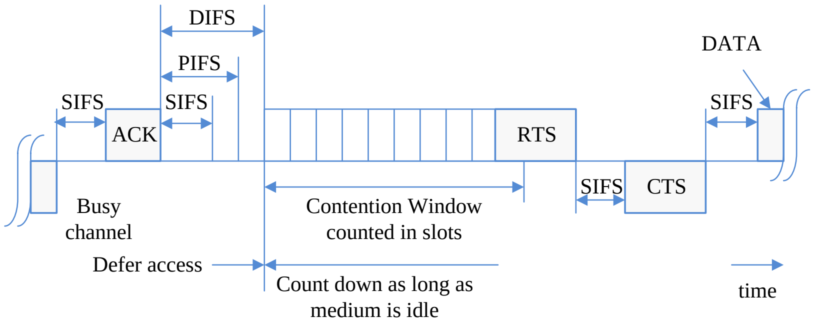


Figure 2.4: Timing and contention-based channel access of IEEE 802.11

Point Coordination Function Interframe Space (PIFS) and Distributed Coordination Function Interframe Space (DIFS). The shorter the IFS, the higher is the priority in accessing the medium. The fourth IFS, called Extended Interframe Space (EIFS), is used when a node detects an ongoing transmission as being interfered with, assuming that there are some stations that cannot detect each other.

Collision avoidance and random backoff

If more than one node will attempt to transmit at the same time, a collision happens. To overcome this issue, 802.11 is based on CSMA/CA. In the 802.11, a CA mechanism is defined to reduce the probability of such collisions. Each node performs a backoff procedure before data transmission strats. According to IEEE 802.11, a node that has data packet ready for transmission has to keep sensing the channel for an additional random time duration after detecting the channel as being idle for a duration DIFS. The node is allowed to initiate its transmission only when the channel sensed idle for this time duration. The duration of this random time is determined as a multiple of slot duration (aSlotTime). Each node maintains a so-called Contention Window (CW), which is used to determine the number of slot times a node has to wait before transmission. Figure 2.4 shows an example in which after a successful frame exchange, i.e., after the ACK transmission, a node starts the next frame exchange (RTS frame followed by CTS frame), because the channel has been idle for a duration equal to DIFS and its following backoff slots. The CW size is doubled when a transmission fails, i.e. when the transmitted data frame has not been acknowledged. This reduces the collision probability in case there are multiple stations attempting to access the channel.

Channel reservation

To avoid the well-known problems such as hidden node and exposed node problems, 802.11 allows the optional use of a RTS/CTS mechanism. Before transmitting a frame, a node has the option of transmitting a short RTS frame, which must be followed by a CTS frame transmission by the receiving node. Between two consecutive frames in the sequence of RTS, CTS, data, and ACK, a SIFS gives transceivers time to turn around. It is a decision made locally by the transmitting node, whether or not RTS/CTS handshake is used.

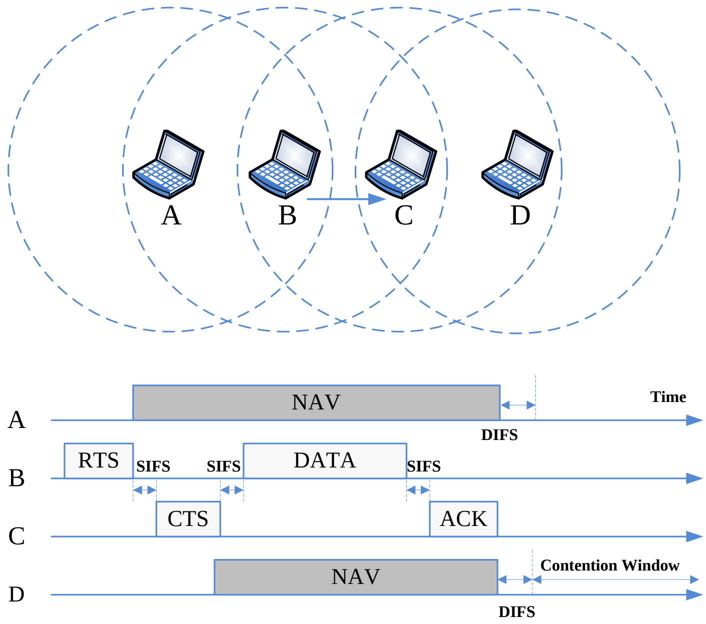


Figure 2.5: Operation of IEEE 802.11 DFC MAC

The RTS and CTS frames include information of how long it takes to transmit the next data frame, e.g., the first fragment, and the corresponding ACK frame. Hence, other nodes close to the transmitting nodes and the hidden nodes close to the receiving node will not start any transmissions; their NAV timer is set. A hidden node close to the receiving station might not receive the RTS due to the large distance, but will in most cases receive the CTS frame. Figure 2.5 presents an example of the DCF using RTS/CTS. It is important to note that SIFS is shorter than DIFS, which always gives CTS and ACK the highest priority for access to the channel.

2.4.3.2 Masked node problem as one of the IEEE 802.11 MAC challenges

Although the RTS/CTS mechanism was introduced to eliminate the hidden node and exposed node problems, it introduces a new problem called the masked node problem. According to [22], the masked node can be defined as follows: "a node that is supposed to receive an RTS or a CTS packet, but cannot interpret it correctly because of another ongoing transmission". A masked node can subsequently cause data collisions, even if the RTS/CTS handshake is performed successfully between a transmitter and a receiver. Since data collisions reduce throughput and increase delay, masked nodes may significantly affect network performance.

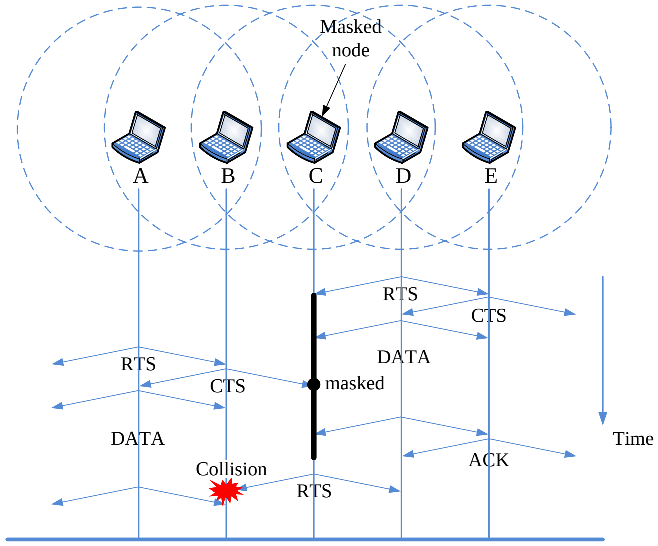


Figure 2.6: The masked node problem

Figure 2.6 show a possible scenario for the masked node problem. In this figure, nodes A, B, C, D, and E represent an ad hoc network arranged in a linear topology. Initially, we assume that all nodes are idle and none of them is prohibited from transmitting. Now, node D and node E exchange RTS/CTS messages successfully and node D starts sending a data packet to node E. Node C receives the RTS sent by node D and updates its NAV appropriately. After node D starts transmitting the data packet, node A sends a RTS to node B. Since node B is not within node D's transmission range, it does not sense any carrier and responds with a CTS. This CTS should reach node C.

However, node C is masked by the signal from node D. Thus, node C cannot decode the CTS packet. Node A, on the other hand, does receive the CTS and, thus, starts sending its DATA packet. In the mean time, nodes D and E complete their communication and node C becomes free to transmit. Node C now transmits a RTS destined for one of its neighbors. This RTS reaches node B and destroys the data packet that node B is receiving.

To reduce the impact of the masked node problem, we have presented a collision reduction mechanism in [18]. The aim of this mechanism is to reduce the collision probability that is caused by the masked node problem. This mechanism extends the IEEE 802.11 DCF by adding a new control packet called Time To Mask (TTM), as shown from Figure 2.7, which contains the time that the node will be masked. This control packet is propagated one hop from the masked node in order to inform the neighboring nodes to be aware of the masked node time

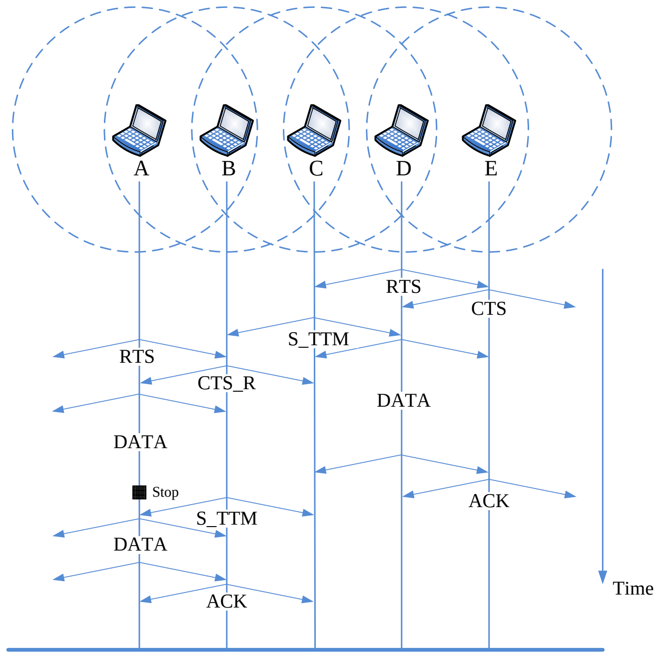


Figure 2.7: RTS/CTS/TTM handshake to overcome the masked node problem

during their transmissions. They can stop their transmissions and resume it again if there is a need for that. The proposed mechanism has been evaluated based on a mathematical analysis and simulation of a small IEEE 802.11 ad hoc network. The results indicate that the proposed mechanism reduces the probability of data packet collision by 38% compared to the original IEEE 802.11 MAC.

2.4.4 Multichannel MAC protocols

In single channel MAC protocols, all nodes share a single channel. Thus, the operations of such protocols are prone to inefficiencies at heavy load. Obviously, this will lead to increase data collisions. Furthermore, with possible unsynchronised backoff delays, the medium can be idle if all contending nodes are in backoff. In addition, any node overhearing RTS or CTS must defer until the end of the entire exchange, which means that concurrent transmissions cannot take place when two transmitters hear each other, even though the respective receivers do not hear any device other than their respective transmitters (the so called exposed node problem).

In contrast, multichannel MAC protocols reduce collisions and enable more concurrent transmissions and thus the overall throughput will be increased. Multichannel MAC protocols allow a number of nodes in the same neighborhood to transmit concurrently on different channels without interfering with each other. Carrier sensing can be coupled with an efficient channel selection mechanism to pick the suitable channel for transmission. Multichannel MAC protocols for wireless ad hoc networks are classified according to [17] and [23] as follows:

1. Dedicated Control Channel: in this class, one dedicated channel is used to transmit control messages while the other channels are used as data channels. Each node has two transceivers, so that it can use one for listening to control messages on the control channel and the other for transmit/receive data on the data channels simultaneously. RTS/CTS packets are exchanged on the control channel, and data packets are transmitted on the data channel. In RTS packets, the transmitter includes a list of preferred channels. On receiving the RTS, the receiver decides on a channel and includes the channel information in the CTS packet. Then, DATA and ACK packets are exchanged on the agreed data channel. Examples of this approach include Dynamic Channel Allocation (DCA) [24] and DCA with Power Control [25]. The pros of these protocols:1) they does not need synchronization and 2) they can use multiple channels with little control message overhead. However, assigning one channel for control message can be costly when the number of channels is small e.g. in the case of IEEE 802.11b, only three channels are available, and so having one control channel results in 33% of the total bandwidth as the control overhead.

2. Common Hopping: in this class, the nodes hop from one channel to another according to a predefined hopping pattern. When two nodes agree to exchange data by an RTS/CTS handshake, they discontinue hopping and stay on the current frequency for the communication. Other nodes continue hopping, and more than one communication can take place on different frequency hops. After finishing, the transmitter and receiver return back to the original hopping pattern. In this class, each node used only one transceiver. The channel hopping multiple access (CHMA) protocol [26] is an example of this class. The pros of this class: 1) No dedicated control channel and all channels are used for data communications and 2) each node utilizes one transceiver which reduces the hardware cost for the node. However, this class requires synchronization among all nodes in the networks to hop between all channels.

3. Split Phase: in this class, the time is divided into phases such as control and data phases. During the control phase, all nodes tune to the control channel and attempt to make agreements for channels to be used during the following data exchange phase. After a successful transmission of control messages, data transmission takes part during the data phase. In this class, each node used only one transceiver. Examples of this approach are Multichannel MAC (MMAC) [27] and Multichannel Access Protocol (MAP) [28]. The pros of this class are that it requires only one transceiver per node. However, it requires time synchronization among all devices, although the synchronization can be looser than in common hopping because devices hop

less frequently.

4. Multiple Rendezvous: in this class, each node picks a seed to generate a different random hopping sequence. When a node is idle, it follows its home hopping sequence. Each node puts its seed in every packet that it sends, so its neighbours eventually learn its hopping sequence. Afterward, the nodes start RTS/CTS handshake and stop hopping to exchange data. After the data exchange is over, both nodes return to their original hopping sequence. In this class, one transceiver is used by each node. Examples of this approach include Slotted Seeded Channel Hopping (SSCH) [29] and Multi-channel MAC (McMAC) [30].

Although multichannel MAC protocols are designed to reduce the collision and thus increase the overall throughput for ad hoc networks, the growing proliferation of ad hoc devices and the limited number of channels in the unlicensed band is limiting these enhancements. Thus, new spectrum concepts are needed to increase the number of the channels for the ad hoc devices in the future. The next section presents an overview of those concepts and how it will be used to improve the performance of ad hoc networks.

2.5 Spectrum availability for ad hoc networks: the future

Due to the rapid growth of wireless communications, a tremendous number of different communication systems use unlicensed bands, supporting different demands and applications such as IEEE 802.11, Bluetooth, Zigbee, etc. as introduced in Section 2.4. Thus, the unlicensed bands are often quite crowded. On the contrary, the licensed bands like those assigned to analogue cellular telephony or TV bands are underutilized. Therefore, new solutions are needed to utilize the available spectrum more efficiently. One easy solution is to increase the spectrum for the unlicensed bands. However, this solution is very difficult and takes a long time for the regulators. Another solution is to allow secondary wireless networks to access the unused spectrum from the licensed bands opportunistically; therefore its overall utilization would dramatically increase. This solution called OSA. OSA is a spectrum management concept proposed as a solution to the problem of current inefficient spectrum usage. A reader will notice some inconsistency in terminologies related to OSA, e.g., what is the relation between CR, DSA and OSA. In the following section we will try to clarify the inconsistency and the ambiguity in the terminologies related to OSA.

2.5.1 Dynamic spectrum access

The current spectrum management policy is static. On the opposite direction, the term DSA has broad connotations that encompass various approaches to

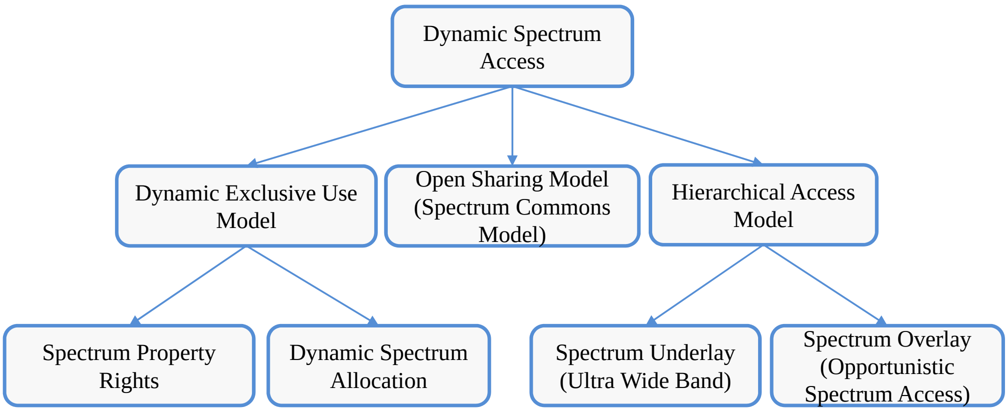


Figure 2.8: A taxonomy of dynamic spectrum access, see [11]

spectrum reform [11]. The diverse ideas presented at the first IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) suggest the extension of this term. Recently, the IEEE Standards Coordinating Committee (SCC) 41 initiates a series of standards on next generation radio and advanced spectrum management. One of those standards is the IEEE P1900.1 standard [31]. The main purpose of this standard is providing technically precise definitions and explanations of key concepts in the field of spectrum management. The standard defines the DSA as follows:

> **Dynamic Spectrum Access (DSA):**
> *The real-time adjustment of spectrum utilization in response to changing circumstances and objectives.*

DSA strategies, as illustrated in Figure 2.8, can be broadly categorized under three models: dynamic exclusive use, open sharing and hierarchical access [11][32].

2.5.1.1 Dynamic exclusive use model

This model gives each user or provider an exclusive use of the licensed spectrum, but differs from a static assignment in the sense that the channels are allocated dynamically among possible licensees. Exclusive channel access is usually governed by radio regulation bodies. Two approaches have been proposed under this model:

- Spectrum property rights [33]: this approach allows licensees to sell and trade spectrum and to freely choose technology.
- Dynamic spectrum allocation [34]: this approach was brought forth by the European DRiVE project. It aims at improving spectrum efficiency through

dynamic spectrum assignment by exploiting the spatial and temporal traffic statistics of different services.

2.5.1.2 Open sharing model

This model is also named spectrum commons. In this model, different users compete for the assigned frequencies on equal terms. Advocates of this model draw support from the phenomenal success of wireless services operating in the unlicensed ISM band.

2.5.1.3 Hierarchical access model

This model adopts a hierarchical access structure between the licensed user or PUs and the unlicensed user or SUs. The basic idea is to open licensed spectrum to the SUs while limiting the interference perceived by the PUs. Two approaches to spectrum sharing between PUs and SUs have been considered:

- Spectrum underlay: an SU can transmit in a band already occupied by a PU if this transmission does not increase the interference to the PU above a given threshold. Ultra-Wideband (UWB) is an example for this approach.
- Spectrum overlay: an SU cannot transmit in an already occupied band like the underlay approach. PUs are given the highest priority to access the frequency band, and SUs have to back off when a PU is present. However, in the absence of the PU, the SU can opportunistically use this band. This approach was first envisioned by Mitola under the term spectrum pooling and then investigated by the DARPA XG programme under the term OSA.

Compared to the dynamic exclusive use and open sharing models, the hierarchical model is perhaps the most compatible with current spectrum management policies and legacy wireless systems. This model can be used without changing spectrum regulation. In this dissertation, we will focus only on the spectrum overlay approach from the hierarchical model.

2.5.2 Opportunistic Spectrum Access

The basic concept of OSA is to open licensed radio spectrum to secondary usage while limiting the interference with PUs. It is commonly acknowledged that a concept similar to OSA was first introduced in [35] under the concept of spectrum pooling, which is a resource sharing strategy that organizes and groups available unused spectrum into a common pool and spectrum resources are allocated dynamically to requesting SR systems. The OSA concept has been investigated by the DARPA Next Generation (XG) program as a spectrum management concept which gives the secondary users (SUs) (ad hoc devices) the opportunity to access unused parts of the licensed spectra [5]. According to DSA categories, OSA is categorized as a spectrum overlay approach. Recently, a simple definition for OSA is listed in the IEEE P1900.1 standard [31] as follows:

Opportunistic spectrum access (OSA):
Dynamic spectrum access by secondary spectrum users that exploits local and instantaneous spectrum availability in a noninterfering manner and without primary user negotiation.

2.5.3 Cognitive radio

The key enabling technology for OSA is CR technology. CRs are envisioned to be able to provide a high bandwidth to the SUs via heterogeneous wireless architectures and DSA techniques. The networked CRs also impose several challenges due to the broad range of available spectrum as well as diverse QoS requirements of applications. CR technology is built on the software defined radio (SDR) technology. Wireless devices with SDR can rapidly reconfigure the operating parameters, such as frequency range, modulation type and maximum transmission power according to the surrounding environment. Based on these parameters, the SUs can communicate with each other without interference with the PUs. CR can be applied to any network that suffers from spectrum shortage. Thus, ad hoc networks are the ones that will immensely benefit from additional spectrum capacity that CR can offer.

Different definitions for CR were presented in the literatures. The first definition was introduced by J. Mitola [36][37]. Mitola has defined CR as follows:

Mitola Definition:
The point in which PDAs and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.

In 2005, Simon Haykin [6] has summarized the idea of CR. His definition was more detailed compared to Mitola's definition:

Haykin Definition:
Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment, and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters in real-time, with two primary objectives in mind: (1) highly reliable communications whenever and wherever needed; (2) efficient utilization of the radio spectrum.

Recently, the IEEE P1900.1 standard [31] has defined the CR as:

IEEE P1900.1 Standard Definition:
A type of radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives.

For further discussion about CR in this thesis, we refer to the IEEE P1900.1 standard definitions for DSA, OSA, and CR [31].

2.5.4 Cognitive radio ad hoc networks

Wireless ad hoc networks will potentially benefit from the introduction of the aforementioned spectrum management approaches such as increasing the spectrum capacity for such networks. A wireless device equipped with CR capabilities will be a spectrum aware device and will have the advantage to operate over both licensed and unlicensed bands. In such a case, ad hoc networks called CR ad hoc networks. The main differences between classical ad hoc networks and CR ad hoc networks are the coexistence of SUs with PUs and the wide range of available spectrum which incur substantially different challenges for spectrum sharing in CR ad hoc network. In CR ad hoc networks, an ad hoc device or an SU should perform some spectrum-aware operations, which form a cognitive cycle [8]. The next section will gives an overview about those operations.

2.5.5 Spectrum management operations

There are four main operations that have to combined to make up a fully CR ad hoc networks. These operations, as shown in Figure 2.9, are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [3]. The main feature of each function can be listed as follows:

2.5.5.1 Spectrum sensing

In CR ad hoc networks, the SU should be aware of and sensitive to the changes in its surrounding environment. Therefore, spectrum sensing is an essential for CR networks. Different functionalities, such as PU detection, cyclostationary detection and temperature aware, are required for spectrum sensing. Although spectrum sensing is an essential part of the cognitive cycle, it is not our focus in this dissertation and more details can be found in [7][32].

2.5.5.2 Spectrum decision

After sensing the surrounding environment, a decision should be taken about the best available spectrum band according to QoS requirements of the application. This is called spectrum decision.

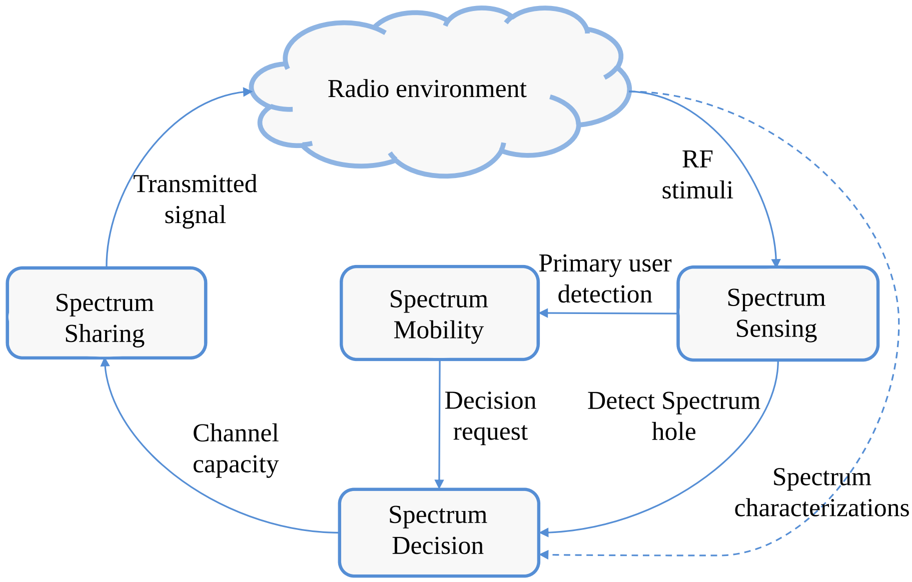


Figure 2.9: The cognitive radio cycle

2.5.5.3 Spectrum sharing

Spectrum sharing provides the capability to maintain the QoS of the SUs without causing interference to the PUs by coordinating the channel access as well as allocating communication resources adaptively.

2.5.5.4 Spectrum mobility

The SUs are generally regarded as visitors to the spectrum. Hence, if the specific portion of the spectrum in use is required by a PU, the communication needs to be continued in another vacant portion of the spectrum. This notion is called spectrum mobility. Spectrum mobility is closely related to time-varying network topologies. Compared to an infrastructure-based network, a CR ad hoc network has a more dynamic and complicated topology depending on both spectrum and user mobility.

2.5.6 Cognitive radio research challenges

Despite the advantage of CR such as increasing the spectrum capacity for ad hoc networks, lots of research challenges still exist and need to be explored. For an ad hoc device to establish a communication according to CR functions, it need to sense the spectrum, decide the best available one, share the spectrum with others and handoff in case of the appearance of PUs. For just one PhD thesis, all the aforementioned functions cannot be covered.

The question was, however, which function needs to be explored. According to our extensive search for the number of publications on IEEExplore library

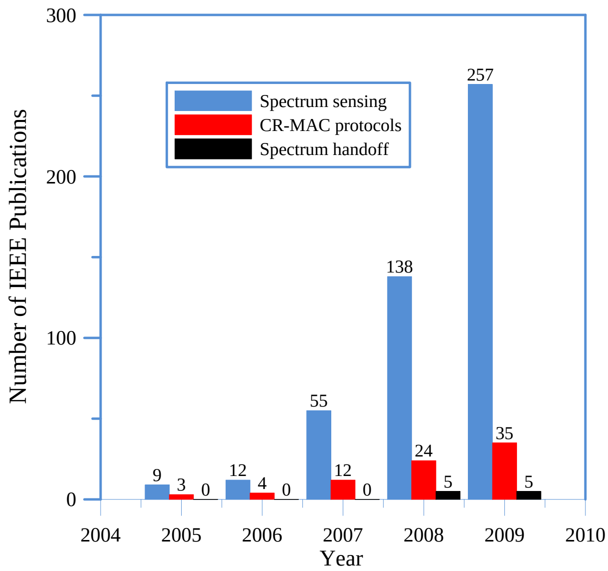


Figure 2.10: The number of articles related to some of CR topics published by IEEE.

since 2005, see Figure 2.10, for topics related to spectrum sensing, spectrum sharing (MAC protocols) and spectrum handoff, it has been found that most of the publications are related to spectrum sensing. There is a gap, however, with respect to the results on CR-MAC protocols and spectrum handoff. Thus, we have decided to cover the CR-MAC protocols and spectrum handoff since they attracted least attention of the research community.

2.5.7 Cognitive radio MAC protocols

CR-MAC protocols include functionality from classical MAC protocols and resource allocation from classical ad hoc networks presented in Section 2.2. However, there are some essential requirements of CR-MAC protocols. These requirements can be listed as follows:

- PU detection: Each SU should distribute the information about the PU activates to other SUs in the network in an efficient way. Thus, the SUs in the vicinity of the PU are aware of its activities when they start transmission.

- Short switching time: The time required for switching from one channel to another in the case of PUs appearance, should be minimized.

- Efficient coordination among the SUs: The SUs should coordinate among each other's to access to the available channels efficiently.

2.5.8 Cognitive radio MAC classification

The existing CR-MAC protocols in the literature can be classified based on the following features:

- Access mode: CR-MAC protocols can be classified based on the channel access mode to random access, time-slotted and hybrid protocols. Random access MAC protocols are based on CSMA/CA principle presented in Section 2.4.3.1. However, one or more features are added to these protocols to be adapted to the CR environment. For random access MAC protocols, no synchronization is needed between the SUs to access the available channels. The Hardware-constrained Cognitive MAC (HC-MAC) protocol [38] and the DCA-MAC protocol [39] belong to this class.

  Time-slotted MAC protocols need a global synchronization between SUs. Therefore, the time is divided to slots for both the control channel and the data transmission. The Cognitive MAC (C-MAC) protocol [40] and the Opportunistic Spectrum Access (OSA-MAC) protocol [41] are CR-MAC protocols belonging to this class.

  Hybrid MAC protocols use a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots. However, the following data transmission may have random channel access schemes, without time synchronization. The Opportunistic Spectrum MAC (OS-MAC) protocol [42] and the SYNchronized MAC (SYN-MAC) protocol [43] are examples from this class.

- Number of transceivers: The number of transceivers has a significant impact on the power consumption and the hardware cost. Some protocols utilized one transceiver while others use two or more transceivers.

- Common control channel (CCC): For each data packet transmission, the SU transmitter and receiver have to coordinate which channel and time slot they will use for the transmission. This coordination is typically implemented using a CCC. From the reliability viewpoint, this CCC is a very crucial element of the MAC design, since no SU data communication is possible when it is obstructed.

- Operating band: The SU can operate over two different spectrum bands: licensed and unlicensed. In the licensed band, the SUs can access the channels in the absence of the PUs only. If the PU appears in a channel occupied by a SU, the latter should vacate that channel and determine a new one immediately. In the unlicensed band, all SUs have the same right to access the available channels.

In the following section, three MAC protocols will be described according to their access mode. Furthermore, other features such as number of transceivers, CCC and the operating band will be described also for each protocol.

2.5.8.1 DCA-MAC as a random access MAC protocol

The MAC protocols in this class do not need time synchronization, and are based on the CSMA/CA principle.

The DCA-MAC protocol [39] is an example for this class. DCA-MAC utilizes two schemes: spectrum pooling [44] and Distributed Channel Assignment (DCA) [24] (one of the multichannel extensions of the IEEE 802.11 CSMA/CA scheme). Each scheme has its own purpose. Spectrum pooling serves as a physical layer signalling for detection of PUs, while DCA serves as a scheme for data exchange and signalling for coordinating access to the available channels. In this protocol, one CCC is used to transmit control messages while the other channels are used as data channels. One of the candidates for CCC is UWB. Each node is equipped with two transceivers: One transceiver is always tuned to an appropriate traffic channel while the other will perform spectrum scanning and sending or receiving on the control channel.

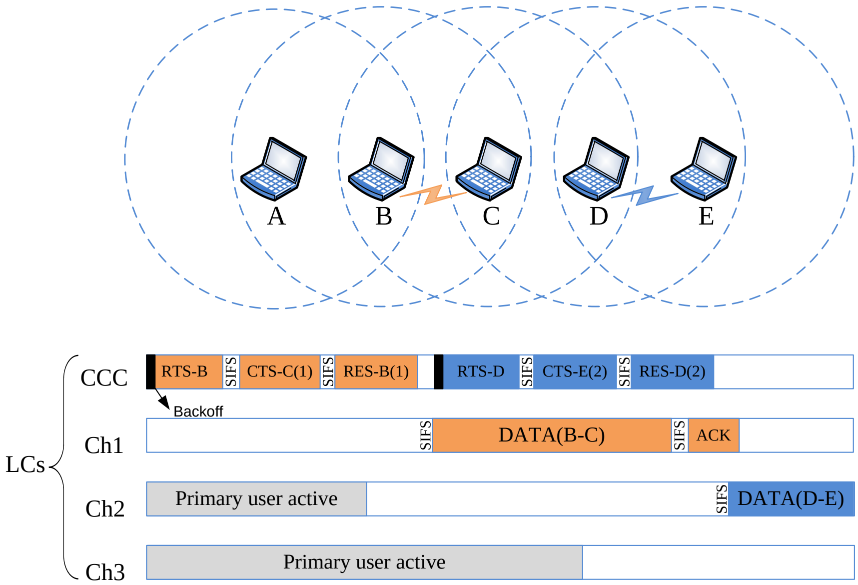


Figure 2.11: DCA-MAC protocol

In DCA-MAC, each node stores two data structures: Current Usage List (CUL) and Free Channel List (FCL). Each node uses spectrum pooling to collect information about the utilization of every channel. This information is stored by other nodes in its CUL. The main idea of the DCA-MAC protocol, as shown from Figure 2.11, can be described as follows. For a node B to communicate with node C, B sends a RTS-B message to C carrying its FCL in the CCC. Upon receiving the RTS, C will match B's FCL with its FCL to identify a data channel (if any) to be used in their subsequent communication. In this example, Ch1 is the result of the matching between the two FCLs. Thus, node C replies with a CTS-C(1) message to B. On receiving C's CTS, B sends a RES-B(1) (Reservation) message to inhibit its neighborhood from using Ch1. Similarly, the CTS will inhibit C's neighborhood from using that channel. Finally, a data packet will be transmitted on the selected data channel (i.e. Ch1). If a PU appears during the data transmission, the packet is lost and a new agreement has to be established between the transmitter and receiver.

The main disadvantage of DCA-MAC is the overhead required to maintain the link in case of PU's appearance. Furthermore, DCA-MAC wastes network resources since it uses channels from the licensed band only and neglects channels from the unlicensed band.

2.5.8.2 OSA-MAC as a time-slotted MAC protocol

In time-slotted MAC protocols, the time is divided into slots for both the control channel and the data transmission. Therefore, network synchronization is needed. OSA-MAC [41] is an example for this class. OSA-MAC assumes a dedicated channel that is used for the exchange of control information between the SUs. This channel is always available (i.e., this channel may be owned by the secondary service provider). This control channel may also be used to transmit data besides control information. OSA-MAC borrows the idea from Power Saving Mechanism in IEEE 802.11 DCF-based WLANs. OSA-MAC assumes that time is divided into beacon intervals. Therefore all SUs will be synchronized by bacons.

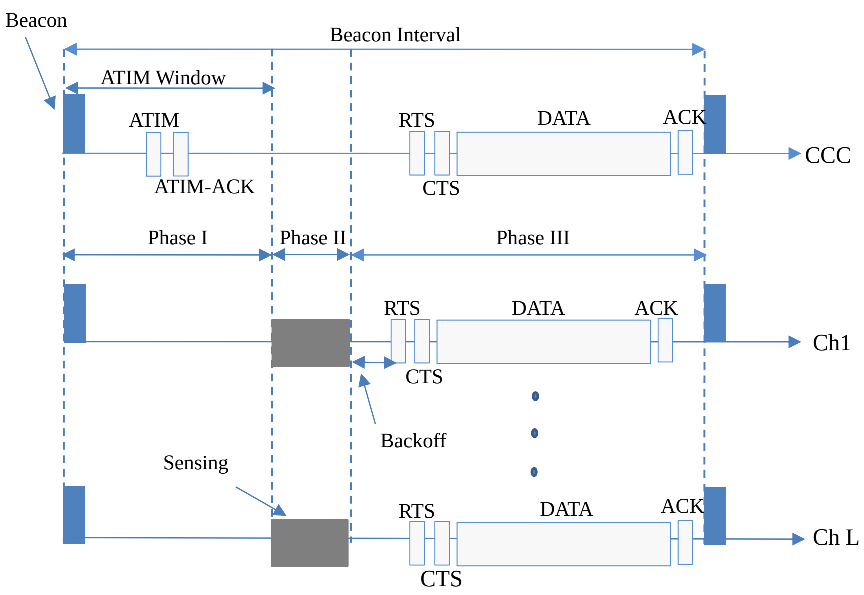


Figure 2.12: OSA-MAC protocol

The OSA-MAC protocol, as shown in Figure 2.12, works as follows. Each beacon interval consists of three phases:

- Phase I: channel selection phase. At the beginning of each beacon interval each SU who wishes to transmit data to its intended receiver will choose a potential channel by transmitting an Ad Hoc Traffic Indication Map (ATIM) to its receiver on the predetermined control channel. Upon receiving the ATIM, the receiver will respond by transmitting an ATIM-ACK to the transmitter. The ATIM will contain the channel chosen by the transmitter for data transmission in phase III.

- Phase II: sensing selection phase. Upon agreeing on the chosen channel, secondary users will switch to their chosen channels for sensing in phase II.

- Phase III: data transmission phase.

OSA-MAC is not reacting efficiently to the PU's appearance. This is one of the main disadvantages of this protocol. Both transmitter and receiver have to establish a new connection every time the PU appears. Furthermore, the OSA-MAC protocol ignores the existence of channels from the unlicensed band when establishing a communication. Moreover, the synchronization is also a challenge.

2.5.8.3 SYN-MAC as a hybrid MAC protocol

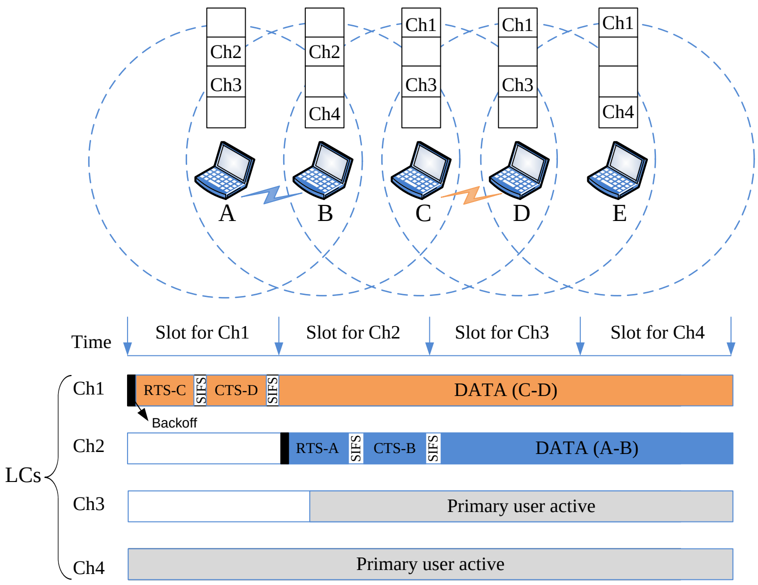


Figure 2.13: SYN-MAC protocol

SYN-MAC [43] is proposed to avoid the CCC. The main idea of SYN-MAC, as shown in Figure 2.13, is to divide total time into fixed-time intervals. Each time slot represents one of the available channels. At the beginning of each time slot, all nodes in the network listen to a channel which the time slot represents for exchanging control signals. Thus, all nodes in the network are synchronized. SYN-MAC is assumed that each node is equipped with two transceivers. One of the two transceivers is used for just listening (listening transceiver) to the control signals and the other for both receiving and transmitting data (data transceiver).

The first node enters the network, divides time into N number of equal time slots of fixed duration, since there are N possible channels. Therefore, each time slot is dedicated to one channel for control signal exchange. This is called network initialization state. Figure 2.13 illustrates a network consists of five nodes A, B, C, D and E. There are four licensed channels, Ch1, Ch2, Ch3 and Ch4. Each node has its own channel list and this list varies from one node to another. To establish a communication between C and D, the following procedure happens:

- There are four time slots, each one representing one channel,
- Two nodes C and D need to communicate, they have two common channels Ch1 and Ch4,
- Node C chooses Ch1 and waits for the beginning of the related time slot, i.e slot for Ch1,
- Node C uses backoff time and starts sending RTS-C to node D,
- Upon receiving the RTS, node D replies with CTS-D,
- Node C starts data transmission to D,
- The same procedure happens when nodes A and B communicates over Ch2,
- In case of the appearance of primary users, C and D vacate the channel.

The main disadvantages of SYN-MAC protocol is the synchronization needed between nodes to access the available channels. The synchronization is really a challenge in an environment lacks the centralized entity like ad hoc networks. Furthermore, the channels availability changes frequently because of PU's appearance, which makes the synchronization more difficult. Moreover, SYN-MAC protocol utilizes channels from the licensed band only and neglects the unlicensed one.

2.5.8.4 Comparison of CR-MAC protocols

In Table 2.1, we present a comparison between the existing CR-MAC protocols. The comparison is done according to the classification presented in Section 2.5.8. The most remarkable observations from the table can be summarized as follows:

1. Most CR-MAC protocols are based on the CSMA/CA mechanism for accessing the available spectrum,
2. Most CR-MAC protocols are using a CCC as a rendezvous channel to exchange control messages,

Table 2.1: Comparison between CR MAC protocols

Protocol	Access mode	Transceiver	CCC	Operating band
HC-MAC [38]	CSMA/CA	One	Yes	Licensed
AS-MAC [45]	CSMA/CA	One	Yes	Licensed
SRAC [46]	CSMA/CA	One	No	Licensed
Hang Su et. al. [47]	CSMA/CA	Two	Yes	Licensed
DOSS [48]	CSMA /CA	Multiple	Yes	Licensed
DCA-MAC [49]	CSMA/CA	Multiple	Yes	Licensed
COMAC [50]	CSMA/CA	Multiple	Yes	Licensed
OC-MAC [51]	CSMA/CA	–	Yes	Licensed
FOSA [52]	CSMA/CA	–	Yes	Licensed
DUB-MAC [53]	CSMA/CA	–	Yes	Licensed
L. Wang et. al. [54]	CSMA/CA	–	No	Licensed
CT-MAC [55]	CSMA/CA	–	No	Licensed
Tao Shu et. al. [56]	CSMA/CA	–	Yes	Licensed
C-MAC [40]	Time-slotted	One	Yes	Licensed
OSA-MAC [41]	Time-slotted	One	Yes	Licensed
MMAC-CR [57]	Time-slotted	One	Yes	Licensed
OS-MAC [42]	Hybrid	One	Yes	Licensed
POMDP [58]	Hybrid	–	No	Licensed
SYN-MAC [43]	Hybrid	Two	No	Licensed

3. All CR-MAC protocols listed in this table are using channels from licensed band as operating channels (i.e., data channels) and ignoring unlicensed band,

Furthermore, the way that these protocol copes with the sudden appearance of PUs, is not efficient. In the case of PU appearance, the data transmission stops and new agreement has to be established between the transmitter and the receiver to maintain the SU's link. Thus, they increase the coordination overhead in the network. In the table, the dash (–) means that this issue is not discussed by the authors.

2.5.9 Spectrum handoff

Spectrum handoff is one of the challenges in CR ad hoc networks. Spectrum handoff occurs when a PU appears in the same channel that is occupied by an SU. In such a case, the SU should vacate this channel and handoff to another free one. This process is continuing till the SU finishes its transmission. The concept of spectrum handoff in CR ad hoc networks is different from the traditional handoff mechanisms in wireless networks. In spectrum handoff, two types of users with different priorities are considered. The high priority users, i.e. the PUs have the right to access the LCs and thus interrupt the transmission of the low priority users, i.e. the SUs and force them to leave the channel even though the signal strength of the low priority user is still acceptable. In the traditional handoff, all users have the same priorities to access the available channels and the decision of changing channels is made mainly due to the impairment of the current channel signal quality or due to node mobility.

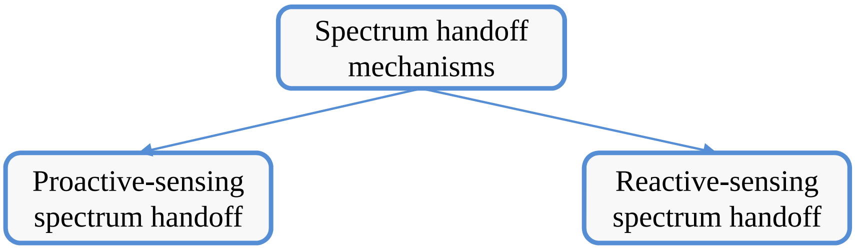


Figure 2.14: Spectrum handoff mechanisms

Spectrum handoff mechanisms, as shown from Figure 2.14, can be categorized into: (1) proactive-sensing spectrum handoff; and (2) reactive-sensing spectrum handoff.

- In the proactive spectrum handoff [59][60], a candidate list of the target channels that can be used in case of the appearance of the PUs is determined by the SU. This list is initiated before the SUs' transmission and updated periodically.
- In the reactive spectrum handoff [61][62], the target channel for the spectrum handoff process is determined on demand by the SUs.

According to [8], the SUs in (neXt Generation) XG networks can operate in both licensed and unlicensed bands. However, the spectrum handoff is done only in the licensed band for all the previously mentioned classes. None of those classes performs the spectrum handoff in the unlicensed band. The possibility (even if small) that the unlicensed band may become free is not taken into their consideration when designing these spectrum handoff mechanisms. Furthermore, in all the aforementioned studies, the spectrum handoff process has not been comprehensively discussed.

2.6 Chapter summary

In this chapter, an overview of spectrum availability for ad hoc networks is presented. The conclusion from this chapter can be listed as follows:

1. Wireless ad hoc networks are becoming more ubiquitous in terms of devices, application areas, etc. due to their small cost and minimal deployment effort. Since all these networks operate in the unlicensed band, the problems of congestion and spectrum scarcity have arisen.

2. There is an indispensable need for new spectrum management concepts to improve spectrum utilization and support further wireless ad hoc networks.

3. The OSA concept is a powerful candidate to solve the spectrum scarcity problem for classical ad hoc networks. Based on OSA, the unlicensed ad hoc devices or SUs will utilize the unused spectrum in the licensed band without interfering licensed users, i.e. PUs. Once the PU appears in the same channel that is occupied by the SU, the SU should vacate the channel to another free one. Consequently, CR technology has been developed to realize OSA.

4. Despite the advantages of OSA and CR, some problems are still existing such as:

   (a) Spectrum access in OSA networks is neither organized nor well managed. For example, the unlicensed band is mostly considered saturated and thus its usage is discriminated. Thus, a new spectrum management concept is needed for improving spectrum utilization regardless of the fact that the spectrum is licensed or unlicensed.

   (b) To the best of our knowledge and according to the survey presented in this chapter, none of CR-MAC protocols is flexible to operate over channels from both the licensed and unlicensed bands. All of those protocols are designed to operate over licensed channels only as data channels. Furthermore, they are not reacting efficiently to the appearance of PUs. Therefore, a flexible and efficient CR-MAC protocol should be developed to coordinate access to the channels among ad hoc devices regarding the fact that the channels are from licensed or unlicensed bands.

Chapter 3

Opportunistic Spectrum Access with Backup channel (OSAB)

In this chapter, a new spectrum management concept called opportunistic spectrum access with backup channels (OSAB) is presented. The proposed concept is based on using channels from both licensed and unlicensed bands as spectrum environment for ad hoc devices. An analytical model based on Markov chains is developed to evaluate the OSAB concept.

3.1 Introduction

Radio spectrum is a limited natural resource and with the increasing number of wireless devices, an efficient spectrum management concept to make a better utilization of this resource is essential. OSA, as presented in Chapter 2, seems to be a powerful solution to increase the spectrum capacity and thus reducing the data collision for wireless ad hoc networks. However, (i) networks based on OSA are accessing the licensed band only, the unlicensed band for them are always saturated and therefore the effect of this band is neglected, (ii) the spectrum handoff process in OSA networks is a time consuming process since an SU should establish a new agreement with its receiver each time the PU appears which increases the control messages overhead.

In this chapter, a new spectrum management concept called OSAB is introduced to overcome the aforementioned problems. The proposed concept aims to provide secondary users (SUs) (e.g. classical ad hoc users) with the ability of adaptively and dynamically seeking and exploiting opportunities in both licensed channels (LCs) and unlicensed channels (UCs) without interference with the legacy users or the primary users (PUs). Moreover, OSAB is based on using a backup channel (BC) as a response to the appearance of PUs. The proposed concept is extensively evaluated using a Markov chain model and compared to existing spectrum management approaches such as OSA.

This chapter is organized as follows: In Section 3.2, an overview of the OSA concept is provided. The OSAB concept is presented in Section 3.3. In Section 3.4, a survey about the existing analytical models is given. Section 3.5 presents the assumptions for the analytical models. In Sections 3.6 and 3.7, extensive analytical models based on Markov chain for both OSA and OSAB are developed, respectively. Finally, the numerical results are discussed in Section 3.8.

3.2 Opportunistic spectrum access

In Chapter 2, different categories of DSA were introduced. Based on these categories, opportunistic spectrum access (OSA) is an overlay approach under the hierarchical access model.

The term spectrum opportunity has been clarified in [63]. The authors have illustrated simply that a channel can be considered as an opportunity when it is

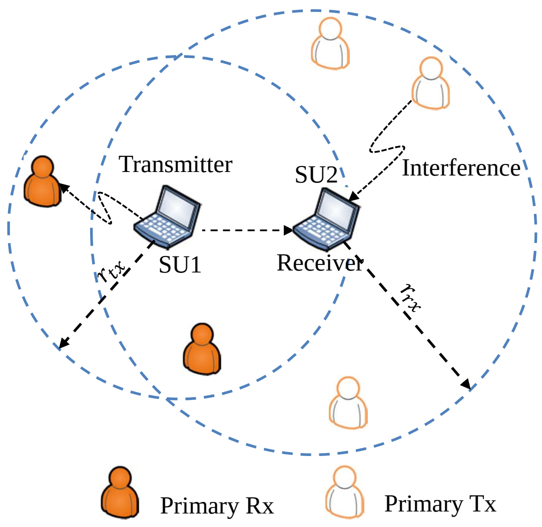


Figure 3.1: Spectrum opportunity

not currently used by PUs. For a channel to be considered as an opportunity, some conditions should be hold. Figure 3.1 depicts these conditions. From Figure 3.1, a channel is an opportunity for both SU1 and SU2, if no PUs, within a distance of r_{tx} from SU1, are receiving and no PUs, within a distance of r_{rx} from SU2, are transmitting over this channel. Based on the aforementioned definition of spectrum opportunity, the SUs can access this opportunity without interfering with the PUs and thus the spectrum capacity for the SUs will be increased. In [64], the authors have introduced the basic idea of OSA. The basic idea of OSA is: a device first senses the spectrum it wishes to use and determines the presence or the absence of PUs. Based on sensing information, the device identifies the spectrum holes or communication opportunities in frequency and time. Therefore, the device will transmit without interfering with PUs.

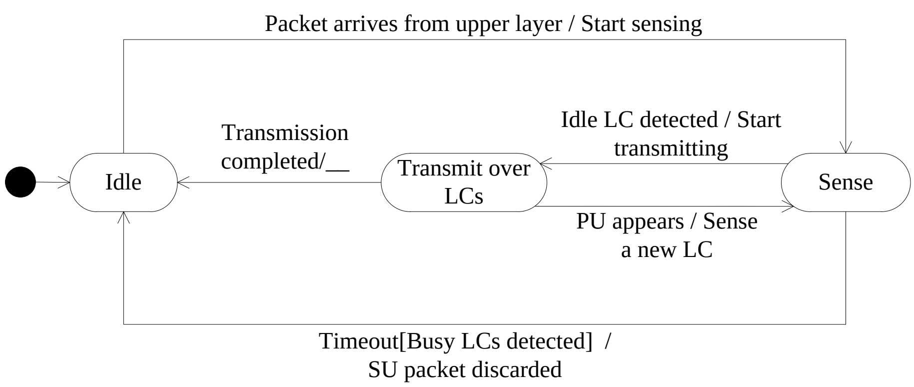


Figure 3.2: State machine for an SU in OSA

According to the basic idea presented in [64] and the OSA definition introduced in Chapter 2, we have designed a state machine using Unified Modeling Language (UML), as shown in Figure 3.2, to describe the behavior of an SU using OSA. In UML, rounded rectangles represent the states the SU can be in, the events under which an object changes state (transitions), the conditions that must be fulfilled before the transition will occur (guards), and the activities undertaken during the life of an object (actions). In summary, the label on a transition is written as follows: Event [*Guard*] /Action. For OSA, the state machine has the following three states: **Idle**, **Sense** and **Transmit over LCs**.

Idle state: Initially, the SU is in the *Idle state* when it has no packet in its queue to send. The transition from the *Idle state* is triggered by the arrival of a packet from the upper layer. As a response, the SU transfers to the *Sense state* to find a free channel to send this packet.

Sense state: In this state, each SU senses the LCs for a predefined time and searches for an opportunity or a channel free from PUs. For this state two triggers are possible: (1) The time for the sensing process is expired and no free LCs is detected. In such a case, the SU gets blocked and transits to the *Idle state* and (2) the SU detects a free LC and the negotiation with its intended transmitter is successful. In such a case, the SU starts data transmission over the LC.

Transmit over LCs state: In this state, the node sends the packet to the physical layer and the data transmission starts. The transition from this state is triggered by 1) a successful data transmission: in such a case, the SU goes to the *idle state* and 2)the appearance of PU: in such a case, the SU performs spectrum sensing to detect a free LC for transmission completion. If there are free LCs, the SU handoffs to another free LC. Otherwise, the SU packet gets dropped.

3.3 Opportunistic spectrum access with backup channel

As mentioned from the previous section, the OSA concept is proposed to increase spectrum capacity for the SUs. However, OSA fails to manage and organize the access to the available spectra (i.e. LCs and UCs) efficiently. For example, the process of selecting an appropriate channel to continue transmission, in the case of the PUs appearance, is a time consuming process in OSA. This process is triggered every time a PU appears. This process is called spectrum handoff. The SU's performance will be affected, if the number of spectrum handoffs is increased. This has motivated us to develop OSAB. OSAB is a modern spectrum management concept developed to manage and organize the access to the available spectra regardless of the fact that the available spectra is LCs or UCs. Furthermore, it uses the principle of BC to reconstruct and maintain the SU link in the case of PUs appearance. This reduces the expected delay required to find a suitable channel to continue transmission.

Table 3.1: Main differences between licensed and unlicensed channels

Channels	**Licensed**	**Unlicensed**
Number of channels	*High*	Low
Access priority	High priority for PUs	*Same priority for all users*
Spectrum utilization	*Low*	High

We took into consideration the specific advantages of LCs and UCs when we have designed OSAB. The main advantage of LCs is the significant number of available channels. For the UCs, the main advantage is that all users have the same rights to access these channels and that there is no preemption for any user once it has obtained the channel. Table 3.1 lists the main differences between LCs and UCs (Words in Italics presents main advantages of each type).

The behavior of OSAB is controlled and affected by different types of channels and users. The channels, as mentioned before, are of two types: LCs and UCs. The users are of three types: PUs which are wireless devices utilizing a licensed band e.g. a TV band. SUs which are wireless devices equipped with cognitive radio capabilities for adaptively and opportunistically accessing the available spectrum (i.e., LCs or UCs). Classical Users (CUs) which are wireless devices without cognitive radio capabilities such as devices using the conventional standards such as IEEE 802.11 and Bluetooth. The idea behind involving CUs is their impact on the UCs since most conventional standards use UCs (such as channels from ISM band) as a spectrum environment.

The main idea of OSAB is

- Utilizing LCs as operating channels for the SUs since the number of available channels is high. By operating channels, we mean channels used for data transmission. The LCs are shared between PUs and SUs with high priority for the PUs to access the channels.
- Utilizing UCs as backup channels in the case of PUs appearance. Since the UCs are shared between SUs and CUs with equal priority, it may happen that all UCs are busy. In such a case, the BC will be selected from the LCs.

Figure 3.3 presents a simple CR ad hoc network based on the OSAB concept. This network coexists with other two networks: Primary network and a classical ad hoc network. The primary network consists of a primary base station and four PUs. Each PU uses a one of the LC for the transmission purpose. The classical ad hoc networks consists of three CUs (CU1, CU2, and CU3) establishing a network in the unlicensed band. The CR ad hoc network consists of three SUs (SU1, SU2 and SU3) establishing an ad hoc networks on the licensed band using channels not utilized by PU3 and PU4. The three layers indicate that all networks located

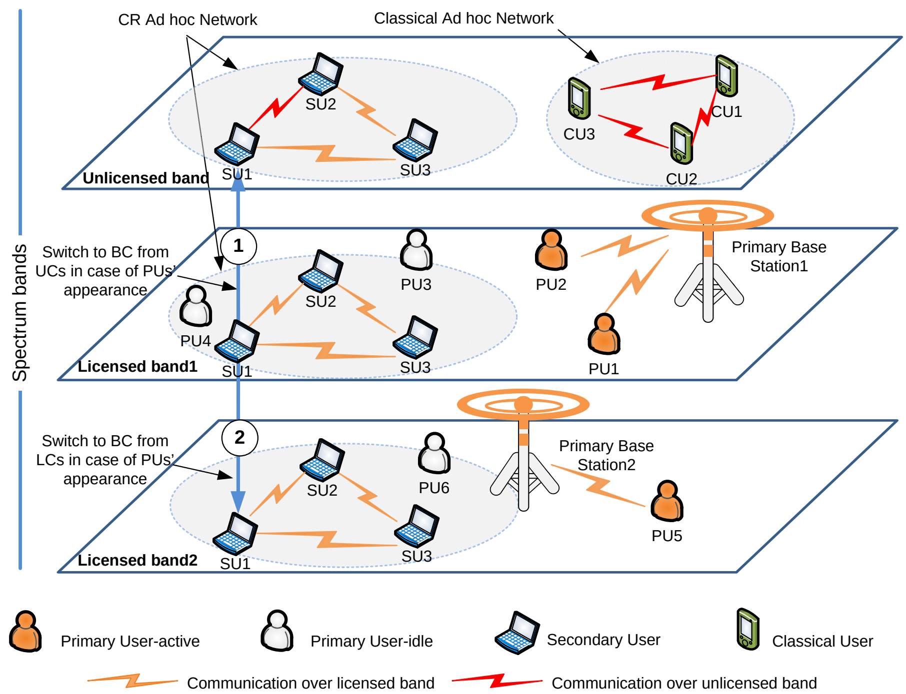


Figure 3.3: A simple scenario for OSAB

in the same area. We assume that PU4 appears and reclaims the channel used by SU1. In such a case, SU1 can perform two actions:

1. SU1 vacates this channel and switches to a channel from the UCs as illustrated by action 1 in the figure. If the selected channel is free, there is no more interruption since the UCs are free from PUs.

2. if there is no UCs available, a free channel will be selected from the LCs as illustrated by action 2 in the figure. In such a case, there is a probability that a new interruption will happen and therefore SU1 will need to vacate that channel again.

As shown in the figure, the OSAB concept is not neglecting the existence of the UCs when an SU performs a spectrum handoff. Each time a PU appears, the SUs should check the spectrum availability on the UCs. If the SU succeeded to obtain an UC in one of those tries, no more spectrum handoffs are needed since the UCs are free from PUs (Point 3, Table 1). If not, the SU performs the spectrum handoff in the LCs.

The behavior of an SU using OSAB can be described in further details by the state machine in Figure 3.4. In addition to the **Idle**, **Sense** and **Transmit over LCs** states described for OSA, a new state named **Transmit over UCs** is added. More details about OSAB state machine can be described as follows:

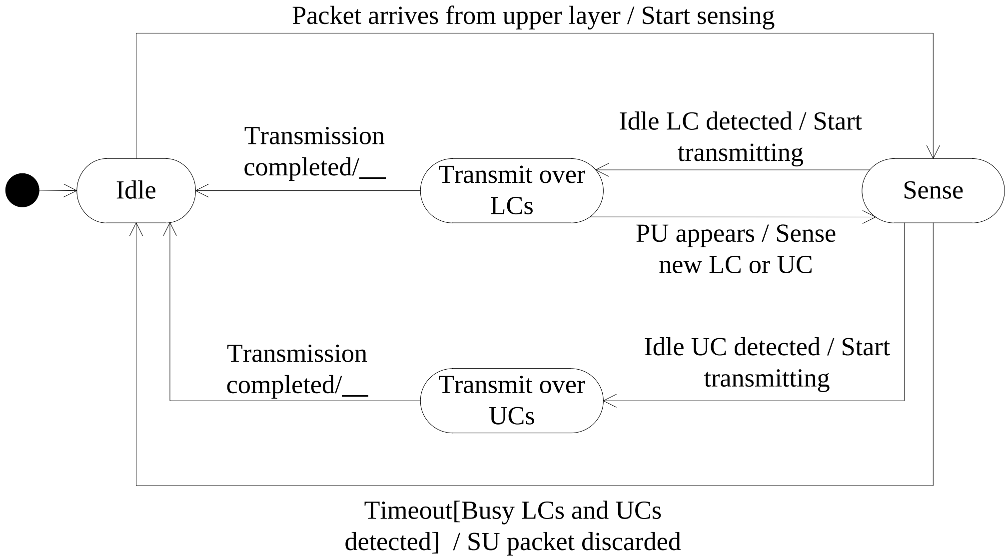


Figure 3.4: State machine for an SU in OSAB

Idle state: Like OSA, the SU is in the *Idle state* when there is no packet available. The transition from this state is triggered by the arrival of a packet from the upper layer. As a response, the SU transits to the *Sense state* to find a free channel to send this packet.

Sense state: In this state, each SU senses both LCs and UCs for a predefined time and determines the spectrum holes or channels free from PUs. Based on the sensing information, each SU constructs a map about the available LCs and UCs. The SU sorts the LCs according to the activities of PUs in a table. For this state three triggers are possible: (1) The time needed for the sensing process is expired and no free channel (LC or UC) is detected. In such a case, the SU gets blocked and switches to the *Idle state*, (2) the SU detects a free LC and the negotiation with its intended transmitter is successful. In such a case, the SU starts data transmission over the LCs and (3) the SU detects a free UC and the negotiation with its intended transmitter is successful (this event happens only if no LC is detected by SU). In such a case, the SU starts data transmission over the LCs.

Transmit over LCs state: In this state, the SU sends the packet to the physical layer and the data transmission starts. Two triggers are possible for this state: (1) a successful data transmission or, (2) the appearance of PUs. In the former, the SU goes to the *Idle state*. In the latter, the SU performs spectrum sensing to detect a free LC or UC for transmission completion. If there is a free LC, the SU handoffs to such channel and transits to the *Transmit over LCs state* again. If there is a free UC, the SU handoffs to such channel and switches to the *Transmit over UCs state*. Otherwise, the SU packet gets dropped.

Transmit over UCs state: In this state, the SU continues its transmission over the UCs. In such a case, the SU's transmission continues without interruption since the UCs are free from PUs.

From the aforementioned description for OSA and OSAB, the main differences can be listed as follows:

1. Flexibility: Compared to OSA, OSAB is flexible to operate over the LCs and the UCs,

2. Efficient spectrum utilization: Compared to OSA, OSAB manages and organizes the access to the available spectrum efficiently. It takes into consideration the existence of different users such as PUs, SUs and CUs. Thus, it provides somehow a load balancing for all users to access the available spectrum,

3. Efficient spectrum mobility: Compared to OSA, the concept of BC in OSAB gives the SU the opportunity to establish a fast spectrum handoff.

In the next sections, the performance of both concepts is evaluated based on Markov chains models. Firstly, we start with an overview about the existing analytical models in the literature.

3.4 Related work on analytical models

Markov chain techniques provide very flexible, powerful, and efficient means for the description and analysis of dynamic system properties. A Markov chain consists of a set of states and a set of labeled transitions between the states. A state of the Markov chain can model various conditions of interest in the system being studied. Due to the dynamics of OSA and OSAB, Markov chain seems to be a powerful candidate to evaluate such systems.

In this section, we give an overview about the existing analytical models for OSA networks. In these models, the SUs are accessing the unused spectrum of PUs opportunistically. In the case of PU appearance, the transmission of the SU stops until another free LC becomes free, otherwise the SU drops. According to our extensive survey, we classify the analytical models into two classes based on the performance metrics used for evaluating the system: General models and Special models

General models: This type of analytical models is used to calculate well known performance metrics such as blocking probability and dropping probability. In addition, some solutions are proposed to reduce the previously mentioned metrics. Examples of this class are [65], [66], [67] and [68].

In [65], a Markov chain analysis for spectrum access to LCs only has been presented. In addition, a simple channel reservation scheme for SUs has been proposed for reducing the dropping probability in the case of PU appearance.

Their scheme is based mainly on reserving some channel exclusively from LCs for SUs to perform spectrum handoffs. However, there are three shortcomings in this analysis: 1) the incorrect definition of dropping (forced termination) probability, 2) an incorrect and incomplete Markov chain diagram, and 3) the reserved channels for spectrum handoff are wasting of network resources when they are not used.

In [66], a spectrum sharing scheme for SUs coexisting with PUs has been evaluated through a three-dimensional Markov chain model. The SU performance has been investigated in terms of the blocking and dropping probability with different PU traffic load conditions. Furthermore, a simple reservation scheme for PUs has been developed. In this scheme, some channels are reserved by primary systems for their users. Thus, those channels can not be utilized by the SUs even if they are idle. The aim of the reservation scheme is to reduce the dropping probability of SUs. However, there are three shortcomings in this analysis: 1) the blocking probability is increased since there are some channels which are exclusively used by PUs, 2) the spectrum handoff process is not considered in their model, and 3) some of the transition probabilities in their transition diagram are incorrect which leads to incorrect calculation of the balance equations.

In [67], dynamic spectrum access schemes in the absence or the presence of buffering mechanism for the SUs have been proposed and analyzed. With buffering, they mean that instead of blocking the incoming SUs when the channels are busy, they have assumed that SUs inserted into a buffer until the channel(s) become idle. A Markov approach is developed to analyze the proposed spectrum sharing policies with generalized bandwidth size in both primary system and secondary system. The blocking probability, interrupted probability, forced termination probability and non-completion probability are the main performance metrics in this work. However, there are two shortcomings in this analysis: 1) this approach only uses the buffer for the new SUs not for the interrupted one, and 2) the spectrum handoff process is not considered in their model.

In [68], a spectrum sharing scheme with buffering for new SUs and interrupted SUs has been proposed. Markov model is used to describe and analyze the performance of the proposed scheme. However, there are two shortcomings in this analysis: 1) the spectrum handoff process is not considered in their model and 2) a pool of LCs only was used.

In [69], we have presented the basic idea of OSAB. However, a detailed analytical model was not presented in this work.

Special models: This type is used to evaluate OSA networks in terms of specific performance metrics related to the spectrum handoff process only. Despite its negative impact on SU's performance, the performance evaluation for the spectrum handoff process is less investigated for the OSA network compared to performance metrics from General models. The spectrum handoff process can be classified according to the selection of the target channel to: proactive spectrum handoff and reactive spectrum handoff.

For the proactive spectrum handoff, the SUs determine a candidate list of target channels that can be used in case of PU's appearance. This list is initiated before the SU's transmission. Examples for this approach are given in [59] [70] [71] [72] [73].

In [59] and [70], the authors have presented a CR framework with the capability of performing a packet-by-packet vertical handover to access the radio resources. The basic idea of vertical handover is redirecting the SU's communication stream to a different network without QoS degradation. The main disadvantage of this framework is that the scenario used to describe the model is very simple; it composed only of two independent PU communication links coexisting with an SU.

In [71], the authors have proposed that each SU should have a list of target channels to maintain its communication link in case of PU's appearance. Since the target channels are known for both the transmitter and the receiver, the handoff delay in this case is the channel switching time only. The authors have investigated their model using a preemptive resume priority M/G/1 queueing network. Their results have shown that this model reduce the total service time compared to the randomly channel selection model. However, the target channel list was only selected from the LCs. They have ignored completely the existence of UCs.

In [72], the authors have incorporated a common hopping coordination scheme into the spectrum handoff protocol design. In their model, they have assumed that all SUs are synchronized to hop through channels with the same hopping sequence. Once a link has been established by two SUs, they should pause the channel hopping and remain on the same channel for data transmission. In the case of PUs appearance, both transmitter and receiver hop to the next channel. The results show that the performance of the SU is improved compared to the reactive spectrum handoff. However, synchronization in such a dynamic environment is quite a challenge. The work in [73] is the most related one to our work. The authors have presented a mathematical model to measure the performance of the SUs in terms of the expected number of spectrum handoffs, the link maintenance probability and switching delay. However, in their model, the spectrum handoff is done only in the licensed bands.

For the reactive spectrum handoff, the SUs determine the target channel for the spectrum handoff process on demand. Examples for this class are follows:

In [62] and [74], the authors have presented a new link maintenance algorithm for CR systems. In case of PU's appearance, they assume that each SU needs a time period to perform the following three operations: sensing, selection and negotiation with the receiver to select the new channel. Within their algorithm, the process of selecting a new channel to maintain the SU's link is time consuming. In addition, a detailed performance analysis for their algorithm was not presented.

According to [8], the SUs in XG networks can operate in the LCs and the UCs. However, the spectrum handoff is done only in the LCs for all the previously mentioned approaches. None of those approaches performs the spectrum handoff in the UCs. The possibility (even if small) that the UCs may become free is not taken into their consideration when designing a spectrum handoff mechanism. Furthermore, in all the aforementioned studies, the spectrum handoff process has not been comprehensively discussed.

3.5 Developed analytical models

In this section, we analyze the behaviour of classical OSA and OSAB by means of Markov chain models. Our contribution is three-fold which also represent the major difference from the existing analytical models discussed in Section 3.4.

- Firstly, we present comprehensive analytical models that combine the two models presented in Section 3.4. The developed analytical models extensively analyze the SU performance of OSA and OSAB in terms of six different performance metrics such as the blocking probability, dropping probability, throughput, successful transmission probability, the expected number of spectrum handoffs and effective transmission time,

- Secondly, the transition diagrams, used to evaluate OSA and OSAB, are general and simple state diagrams for all possible states in the system. Our presentation of the transition diagrams gives the reader an easy way to track all possible cases in the system. This is different from other transition diagram from the existing studies for OSA which presents specific cases of the system,

- Thirdly, the proposed analytical model for OSAB analyzes the performance of the SUs in a highly dynamic environment consisting of two different types of channels, LCs and UCs, and three types of users, PUs, SUs, and CUs. This analytical model was firstly presented in [75] and [76].

3.5.1 Common assumptions

The common assumptions for both OSA and OSAB are summarized as follows

1. There are two types of available spectrum (channels), LCs and UCs. OSA utilizes only the LCs and OSAB utilizes both, LCs and UCs.

2. Each LC is assumed to be occupied with PU, and the average PU occupancy level is the same for all channels. Each UC is assumed to be occupied with SU or CU.

3. The maximum number of LCs and UCs are assumed to be C_1 and C_2, respectively.

4. The arrival process of PUs, SUs and CUs are assumed to be Poisson with rates λ_1, λ_2 and λ_3, respectively.
5. The service time of PUs, SUs and CUs are assumed to follow an exponential distribution with expectation $1/\mu_1$, $1/\mu_2$ and $1/\mu_3$ respectively.
6. The SUs are assumed to be completely transparent for the PUs. Therefore, there is no impact of SUs on PUs performance.
7. Immediate preemption of an SU upon the appearance of a PU. In the OSA model, the preempted SU may continue its service if there is a free channel from LCs. In the OSAB model, the preempted SU may continue its service if there is a free channel from LCs or UCs.
8. The SUs under consideration are all homogeneous, i.e. statistically identical and independent.
9. The time needed to perform sensing and decision is assumed to be neglectable.

3.6 OSA model

In this section, we analyze the classical OSA model. In this model, the SUs operate only over the free LCs. If the PU appears, the SU shall immediately handoff from the current channel to another free one. If there is no free LC, the SU is dropped. The SU is dropped, even if there are free UCs. Therefore, the UCs have no effect on the performance of SUs.

3.6.1 System model

In this model, the number of LCs, C_1 is shared between PUs and SUs. Therefore, the process of spectrum access to LCs is fully determined by the pair (i, j) which forms a two-dimensional Markov chain, where

- i: is the number of LCs used by PUs and
- j: is the number of LCs used by SUs.

The state space S for such model is given as

$$S = \{(i, j) \mid 0 \leq i \leq C_1, 0 \leq j \leq C_1 - i\}$$

The system states and the resulting transition diagram for OSA are given by Figure 3.5. The transition diagram has nodes which represent the states the system can be in, and directed arcs which represent the transition between the states. Written next to each transition is the transition rate.

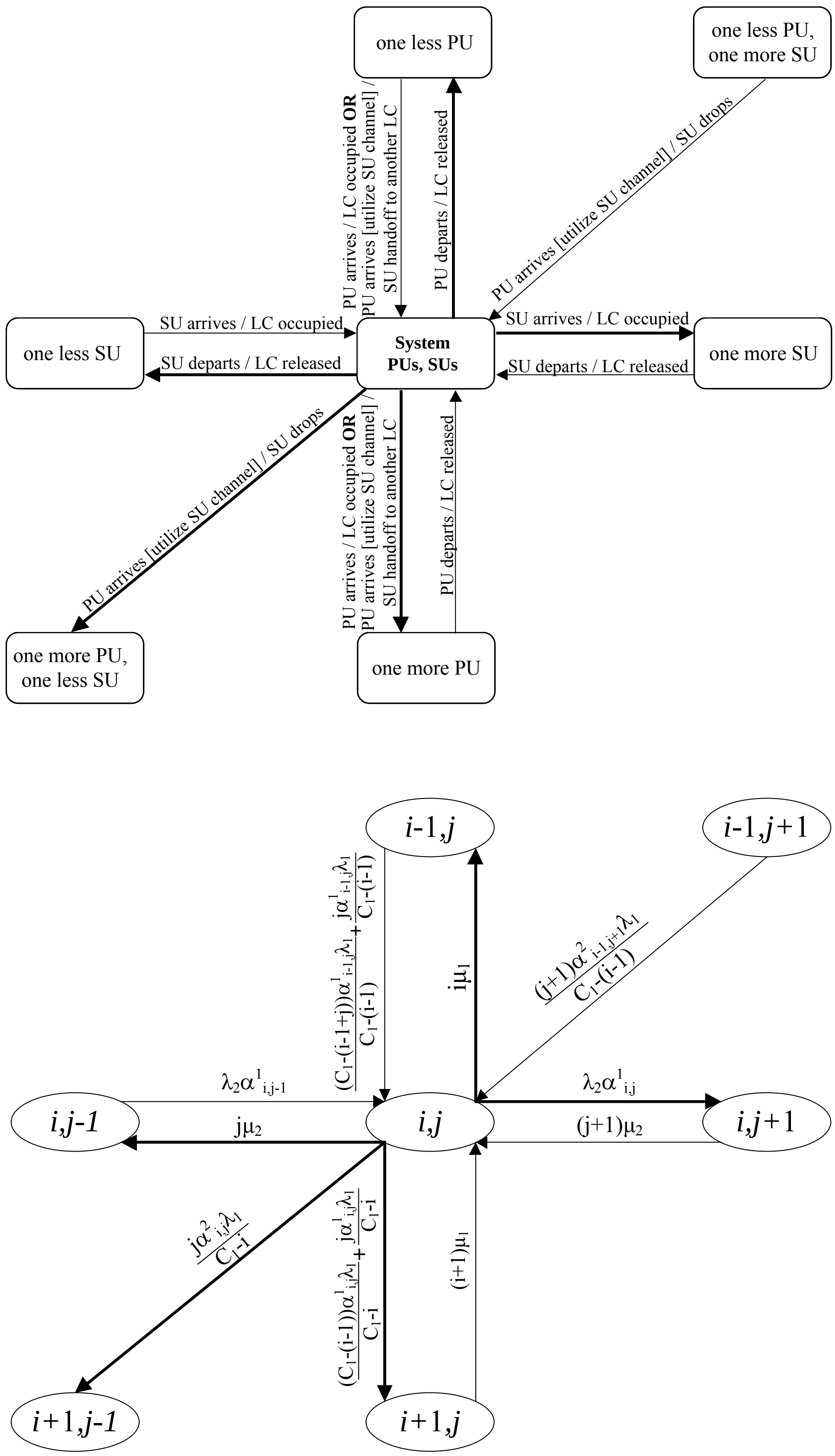


Figure 3.5: System states and the resulting transition diagram for OSA

Let $p_{i,j}$ be the steady-state probability distribution for a state $(i, j) \in S$. In our model, we estimate $p_{i,j}$ using the equilibrium balance equation technique. The equilibrium balance equation can be interpreted to say that the flux out of state (i, j) equals to that into state (i, j). Thus, $p_{i,j}$ can be estimated as follows

$$A_{i,j} p_{i,j} = B_{i,j} \tag{3.1}$$

where $A_{i,j}$ and $B_{i,j}$ describe the flux out and flux in state (i, j), respectively. From Figure 3.5, five states and some events occur to describe the $A_{i,j}$.

1. Transition to state $(i + 1, j)$. This transition happens if one of the two following events happens:

   - a PU arrives AND occupies a free channel with probability $\frac{(C_1-(i+j))\alpha^1_{i,j}}{C_1-i}\lambda_1$. where the indicator variable $\alpha^1_{i,j}$, is given as follows

   $$\alpha^1_{i,j} = \begin{cases} 1 & i+j < C_1 \\ 0 & \text{Otherwise} \end{cases}$$

   - a PU arrives AND occupies a channel which is utilized by an SU. Therefore, the PU preempts the SU from this channel. Furthermore, the preempted SU performs a spectrum handoff to another free LC. The transition rate of this event is $\frac{j\alpha^1_{i,j}}{C_1-i}\lambda_1$,

2. Transition to state $(i+1, j-1)$. This transition happens if a PU arrives AND operates in the same channel that is occupied by an SU. Furthermore, there are no LCs available for the SU to complete its transmission. Therefore, the SU will be preempted and dropped. The transition rate of this event is $\frac{j\alpha^2_{i,j}}{C_1-i}\lambda_1$, where the indicator variable $\alpha^2_{i,j}$, is given as follows

   $$\alpha^2_{i,j} = \begin{cases} 1 & i+j = C_1,\ j > 0 \\ 0 & \text{Otherwise} \end{cases}$$

3. Transition to state $(i, j + 1)$. This transition happens if an SU arrives and operates in a free LC. The transition rate of this event is $\alpha^1_{i,j}\lambda_2$.

4. Transition to state $(i - 1, j)$. This transition happens if a PU completes its service. The transition rate of this event is $i\mu_1$.

5. Transition to state $(i, j - 1)$. This transition happens if an SU completes its service. The transition rate of this event is $j\mu_2$.

The above enumeration explains why in Figure 3.5 there are five arcs going out state (i, j). According to that, the term $A_{i,j}$ can be calculated as follows

$$A_{i,j} = \frac{C_1 - (i + j)}{C_1 - i}\alpha^1_{i,j}\lambda_1 + \frac{j}{C_1 - i}\alpha^1_{i,j}\lambda_1 + \frac{j}{C_1 - i}\alpha^2_{i,j}\lambda_1 + \alpha^1_{i,j}\lambda_2 + i\mu_1 + j\mu_2 \tag{3.2}$$

The term $B_{i,j}$ is calculated analogously from Figure 3.5 as follows.

$$\begin{aligned} B_{i,j} &= \frac{(C_1-(i-1+j))}{C_1-(i-1)}\alpha^1_{i-1,j}\lambda_1 p_{i-1,j} + \frac{j}{C_1-(i-1)}\alpha^1_{i-1,j}\lambda_1 p_{i-1,j} \\ &+\frac{(j+1)\alpha^2_{i-1,j+1}}{C_1-(i-1)}\lambda_1 p_{i-1,j+1} + \alpha^1_{i,j-1}\lambda_2 p_{i,j-1} + (i+1)\mu_1 p_{i+1,j} \\ &+(j+1)\mu_2 p_{i,j+1} \end{aligned} \tag{3.3}$$

Substituting from 3.2 and 3.3 in 3.1, the steady-state balance equation for $p_{i,j}$ is given as follows:

For $0 \leq i \leq C_1$ and $0 \leq j \leq C_1 - i$.

$$p_{i,j} = \frac{\left(\frac{(C_1-(i-1+j))}{C_1-(i-1)} + \frac{j\alpha^1_{i,j}}{C_1-(i-1)}\right)\lambda_1 p_{i-1,j} + \frac{(j+1)\alpha^2_{i-1,j+1}}{C_1-(i-1)}\lambda_1 p_{i-1,j+1} + \lambda_2\alpha^1_{i,j-1}p_{i,j-1} + (i+1)\mu_1 p_{i+1,j} + (j+1)\mu_2 p_{i,j+1}}{\frac{C_1-(i+j)}{C_1-i}\lambda_1 + (\alpha^1_{i,j}+\alpha^2_{i,j})\frac{j}{C_1-i}\lambda_1 + \alpha^1_{i,j}\lambda_2 + i\mu_1 + j\mu_2} \tag{3.4}$$

where $p_{i,j} = 0$ for $i < 0$, $j < 0$ or $i + j > C_1$. To normalize the steady-state probabilities, we have

$$\sum_{i=0}^{C_1}\sum_{j=0}^{C_1-i} p_{i,j} = 1$$

3.6.2 Iterative algorithm

It is a very difficult and complicated process to derive a closed form for $p_{i,j}$ from equation 3.4. Therefore, we used an iterative algorithm that form a successive approximation that converges to the exact solution. The iterative algorithm is adopted to obtain the steady-state probabilities $p_{i,j}$. The iterative algorithm steps can be given as follows:

1. Set a certain convergence threshold κ.
2. Input: C_1, λ_1, λ_2, μ_1 and μ_2.
3. Initialize $p^{old}_{i,j} = 1$ for $i = j = 0$ and $p_{i,j} = 0$ for $i + j > 0$.
4. Compute the probabilities $p^{new}_{i,j}$ using (3.4).
5. If $\left|p^{new}_{i,j} - p^{old}_{i,j}\right| > \kappa$, then set $p^{old}_{i,j} = p^{new}_{i,j}$ and go to Step 4.
6. The steady state probabilities are obtained.

3.6.3 Performance metrics

Once steady state probabilities are obtained, different performance metrics such as blocking probability, dropping probability, and throughput can be derived.

3.6.3.1 SU blocking probability

The SU blocking probability, denoted by $P^1_{block,s}$, is defined as the probability that all the channels in a service area are occupied by either PU and/or SU and no channel is available for a new SU request. Then $P^1_{block,s}$ can be written as follows

$$P^1_{block,s} = \sum_{i=0}^{C_1} p_{i,C_1-i} \tag{3.5}$$

3.6.3.2 SU dropping probability

Dropping represents a disruption of an ongoing SU service. From Figure 3.5, SU dropping will occur resulting in a state transition from (i, j) to $(i + 1, j - 1)$. The dropping probability can be expressed as the total SU dropping rate divided by the total SU connection rate [77][78]. Therefore, the SU dropping probability can be defined as follows

$$\begin{aligned} P^1_{drop,s} &= \frac{\text{Total SU dropping rate}}{\text{Total SU connection rate}} \\ &= \frac{\sum_{i=0}^{C_1-1} \lambda_1 p_{i,C_1-i}}{\left(1 - P^1_{block,s}\right) \lambda_2} \end{aligned} \tag{3.6}$$

3.6.3.3 SUs throughput

The SUs throughput, T^1_s can be defined as the product of connection completion rate, $\left(1 - P^1_{block,s}\right)\left(1 - P^1_{drop,s}\right)\lambda_2$ and the average duration of the successfully completed connections, $\left(\frac{\mu_2}{1-P^1_{drop,s}}\right)^{-1}$. Thus, the SUs throughput T^1_s can be written as follows

$$\begin{aligned} T^1_s &= \left(1 - P^1_{block,s}\right)\left(1 - P^1_{drop,s}\right)\lambda_2 \left(\frac{\mu_2}{1 - P^1_{drop,s}}\right)^{-1} \\ &= \left(1 - P^1_{block,s}\right)\left(1 - P^1_{drop,s}\right)^2 \rho_2 \end{aligned} \tag{3.7}$$

where $\rho_2 = \frac{\lambda_2}{\mu_2}$ is the traffic load. The above definition of throughput is consistent with the conventional definition of throughput (bps) and only considers the completed SUs connections i.e., connections which are neither blocked nor dropped.

3.7 OSAB model

The OSAB model is different from the previous one in the way that an SU is accessing the available spectrum i.e., including LCs and UCs. An SU operates first in the LC and uses it as the operating channels. In the case of PU appearance, we assume that the SU performs immediately handoff to a UC. When there are no free UCs, the SU handoffs to an LC. This is an extension to the work done in [69]. In [69], when a PU appears, an SU performs a spectrum handoff to a channel from the UCs. If there is no free UC, the SU is dropped.

3.7.1 System model

In this model, we assume that the C_1 LCs are shared between PUs and SUs and the C_2 UCs are used as BCs in the case of PU appearance. Furthermore, UCs are used as operating channels by CUs.

The process of spectrum access to LCs and UCs is modelled as a four-dimensional Markov chain (i, j, k, l). Therefore, states in the transition diagram are described by (i, j, k, l), where

- i: is the number of LCs used by PUs,
- j: is the number of LCs used by SUs,
- k: is the number of UCs used by SUs and
- l: is the number of UCs used by CUs.

The state space S is given by

$$\begin{aligned} S &= \{(i, j, k, l) \mid 0 \le i \le C_1, 0 \le j \le C_1 - i, 0 \le k \le C_2 \\ &\quad , 0 \le l \le C_2 - k\} \end{aligned}$$

Figure 3.6 shows system states and the resulting state transition diagram for OSAB. Let $p_{i,j,k,l}$ be the steady-state probability distribution for state $(i, j, k, l) \in S$. From the transition diagram, we estimate $p_{i,j,k,l}$ using the equilibrium balance equations. For $0 \le i \le C_1$, $0 \le j \le C_1 - i$, $0 \le k \le C_2$, and $0 \le l \le C_2 - k$.

$$C_{i,j,k,l} p_{i,j,k,l} = D_{i,j,k,l} \tag{3.8}$$

where $C_{i,j,k,l}$ and $D_{i,j,k,l}$ describe the flux out and flux in state (i, j, k, l) respectively.

From Figure 3.6, ten states and some events occur to describe $C_{i,j,k,l}$:

1. Transition to state $(i + 1, j, k, l)$. This transition happens if one of the following two events happens:

    - a PU arrives AND occupies a free channel. The transition rate for this event is $\frac{(C_1-(i+j))\alpha^1_{i,j,k,l}}{C_1-i}\lambda_1$, where the indicator variable $\alpha^1_{i,j,k,l}$ is given as follows

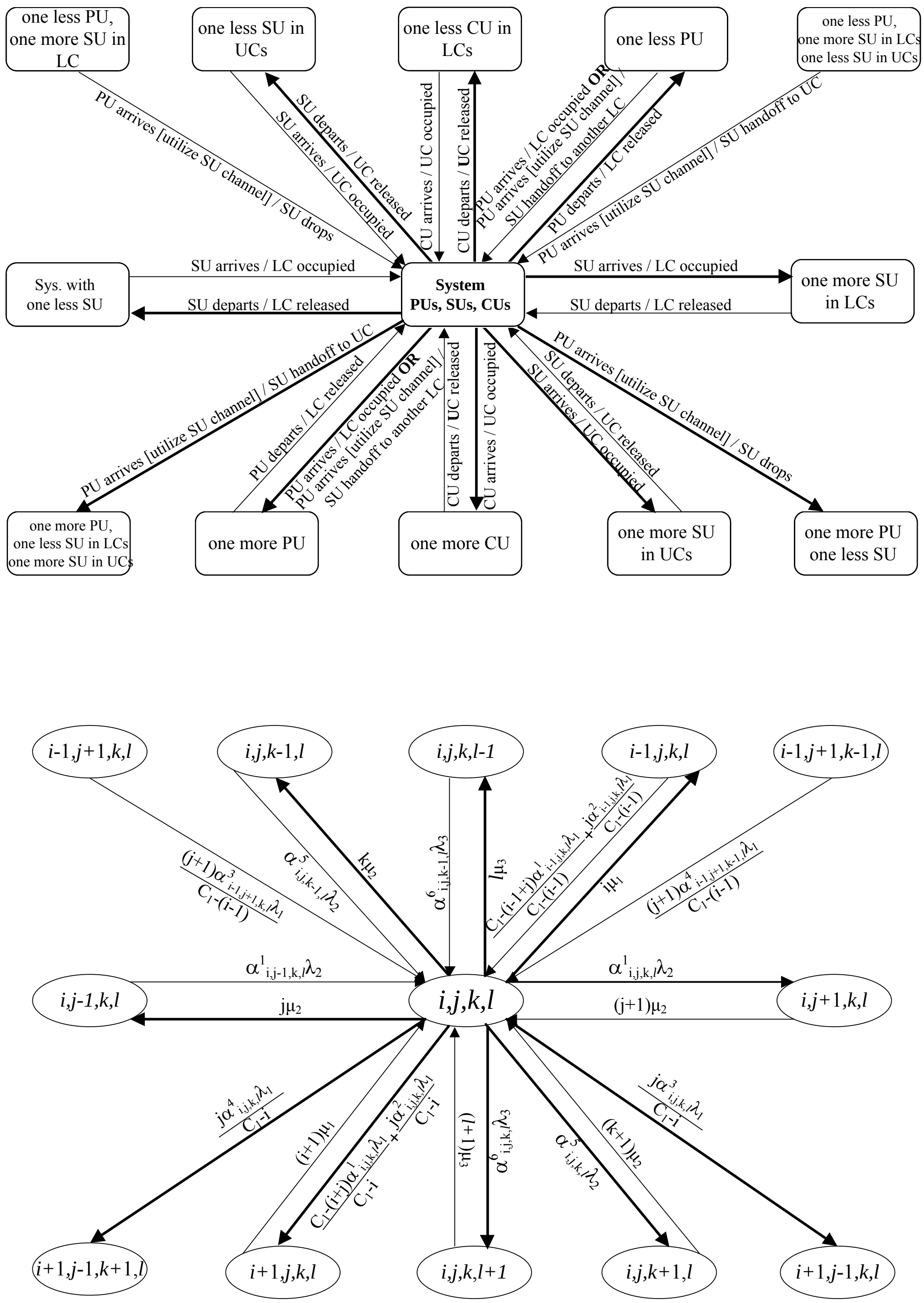


Figure 3.6: System states and the resulting state transition diagram for OSAB

$$\alpha^1_{i,j,k,l} = \begin{cases} 1 & i+j < C_1, k+l \le C_2 \\ 0 & \text{otherwise} \end{cases}$$

OR

- a PU arrives AND occupies a channel which is utilized by an SU. Therefore, the PU preempts the SU from this channel. Furthermore, the preempted SU performs a spectrum handoff to BC from LCs, since there is no available UC. The transition rate for this event is $\frac{j\alpha^2_{i,j,k,l}}{C_1-i}\lambda_1$, where the indicator variable $\alpha^2_{i,j,k,l}$ is given as follows

$$\alpha^2_{i,j,k,l} = \begin{cases} 1 & i+j < C_1, k+l = C_2 \\ 0 & \text{otherwise} \end{cases}$$

2. Transition to state $(i+1, j-1, k, l)$. This transition happens when a PU arrives AND occupies one of the jth SU's channel. Furthermore, there is no available BC from LCs and UCs for the SU to complete its transmission. As a result, the preempted SU will be dropped. The transition rate for this event is $\frac{j\alpha^3_{i,j,k,l}}{C_1-i}\lambda_1$,where the indicator variable $\alpha^3_{i,j,k,l}$ is given as follows

$$\alpha^3_{i,j,k,l} = \begin{cases} 1 & i+j = C_1, k+l = C_2,\ j > 0 \\ 0 & \text{otherwise} \end{cases}$$

3. Transition to state $(i+1, j-1, k+1, l)$. This transition happens when a PU arrives AND occupies one of the jth SU's channels. Furthermore, there is an available BC from the UCs for the SU to complete its transmission. As a result, the preempted SU performs a spectrum handoff to the BC. The transition rate for this event is $\frac{j\alpha^4_{i,j,k,l}}{C_1-i}\lambda_1$, where the indicator variable $\alpha^4_{i,j,k,l}$ is given as follows

$$\alpha^4_{i,j,k,l} = \begin{cases} 1 & i+j = C_1, k+l < C_2,\ j > 0 \\ 0 & \text{otherwise} \end{cases}$$

4. Transition to state $(i, j+1, k, l)$. This transition happens when an SU arrives AND occupies one of the free LCs. The transition rate for this event is $\alpha^1_{i,j,k,l}\lambda_2$,

5. Transition to state $(i, j, k+1, l)$. This transition happens when an SU arrives AND occupies one of the free UCs. The transition rate of this event is $\alpha^5_{i,j,k,l}\lambda_2$, where the indicator variable $\alpha^5_{i,j,k,l}$ is given as follows

$$\alpha^5_{i,j,k,l} = \begin{cases} 1 & i+j = C_1, k+l < C_2 \\ 0 & \text{otherwise} \end{cases}$$

6. Transition to state $(i, j, k, l+1)$. This transition happens when a CU arrives AND occupies one of the free UCs. The transition rate for this event is $\alpha^6_{i,j,k,l}\lambda_3$,

$$\alpha^6_{i,j,k,l}=\begin{cases} 1 & i+j \le C_1, k+l < C_2 \\ 0 & \text{otherwise} \end{cases}$$

7. Transition to state $(i-1, j, k, l)$. This transition happens when one of the ith PUs completes its service and thus the transition rate is $i\mu_1$,

8. Transition to state $(i, j-1, k, l)$. This transition happens when one of the jth SUs completes its service and thus the transition rate is $j\mu_2$,

9. Transition to state $(i, j, k-1, l)$. This transition happens when one of the kth SUs completes its service and thus the transition rate is $k\mu_2$,

10. Transition to state $(i, j, k, l-1)$. This transition happens when one of the lth CUs completes its service and thus the transition rate is $l\mu_3$.

The above enumeration explains why in Figures 3.6 there are ten arcs going out state (i, j, k, l). According to that, the term $C_{i,j,k,l}$ can be calculated as follows

$$\begin{aligned} C_{i,j,k,l} &= \frac{(C_1-(i+j))\alpha^1_{i,j,k,l}\lambda_1}{C_1-i} + \frac{j\alpha^2_{i,j,k,l}}{C_1-i}\lambda_1 + \frac{j\alpha^3_{i,j,k,l}}{C_1-i}\lambda_1 \\ &+\frac{j\alpha^4_{i,j,k,l}}{C_1-i}\lambda_1 + \alpha^1_{i,j,k,l}\lambda_2 + \alpha^5_{i,j,k,l}\lambda_2 + \alpha^6_{i,j,k,l}\lambda_3 \\ &+i\mu_1 + j\mu_2 + k\mu_2 + l\mu_3 \end{aligned} \tag{3.9}$$

The term $D_{i,j,k,l}$ is calculated analogously from Figure 3.6.

$$\begin{aligned} D_{i,j,k,l} &= \frac{(C_1-(i-1+j))\alpha^1_{i-1,j,k,l}\lambda_1}{C_1-(i-1)}p_{i-1,j,k,l} + \frac{j\alpha^2_{i-1,j,k,l}}{C_1-(i-1)}\lambda_1 p_{i-1,j,k,l} \\ &+\frac{(j+1)\alpha^3_{i-1,j+1,k,l}}{C_1-(i-1)}\lambda_1 p_{i-1,j+1,k,l} + \alpha^1_{i,j-1,k,l}\lambda_2 p_{i,j-1,k,l} \\ &+\frac{(j+1)\alpha^4_{i-1,j+1,k-1,l}}{C_1-(i-1)}\lambda_1 p_{i-1,j+1,k-1,l} + \alpha^5_{i,j,k-1,l}\lambda_2 p_{i,j,k-1,l} \\ &+\alpha^6_{i,j,k,l-1}\lambda_3 p_{i,j,k,l-1} + (i+1)\mu_1 p_{i+1,j,k,l} + (j+1)\mu_2 p_{i,j+1,k,l} \\ &+(k+1)\mu_2 p_{i,j,k+1,l} + (l+1)\mu_3 p_{i,j,k,l+1} \end{aligned} \tag{3.10}$$

Substituting from 3.9 and 3.10 in 3.8, the value of $p_{i,j,k,l}$ can be obtained. To normalize the steady-state probabilities, we have

$$\sum_{i=0}^{C_1}\sum_{j=0}^{C_1-i}\sum_{k=0}^{C_2}\sum_{l=0}^{C_2-k} p_{i,j,k,l} = 1$$

3.7.2 Iterative algorithm

The iterative algorithm obtained from Section 3.6, can be modified according to the OSAB concept assumptions. The new algorithm aims to obtain the steady-state probabilities $p_{i,j,k,l}$. The different steps of the new iterative algorithm can be presented as follows:

1. Set a certain convergence threshold κ.
2. Input: C_1, C_2, λ_1, λ_2, λ_3, μ_1, μ_2 and μ_3.
3. Initialize $p^{old}_{i,j,k,l} = 1$ for $i = j = k = l$ and $p_{i,j,k,l} = 0$ for $i + j + k + l > 0$.
4. Compute the probabilities $p^{new}_{i,j,k,l}$ using 3.9 and 3.10.
5. If $\left|p^{new}_{i,j,k,l} - p^{old}_{i,j,k,l}\right| > \kappa$, then set $p^{old}_{i,j,k,l} = p^{new}_{i,j,k,l}$ and go to Step 4.
6. The steady state probabilities are obtained.

3.7.3 Performance metrics

Using the aforementioned iterative algorithm from Section 3.6 with some modification presented by OSAB, different performance metrics can be obtained such as blocking probability, dropping probability and throughput.

3.7.3.1 SU and PU blocking probabilities

An SU gets blocked if upon its arrival, all the LCs and the UCs are occupied. In such a case, the SU blocking probability, $P^2_{block,s}$, can be written as follows

$$P^2_{block,s} = \sum_{i=0}^{C_1} \sum_{j=0}^{C_2} p_{i,C_1-i,C_2-j,j} \tag{3.11}$$

An PU gets blocked if upon its arrival, all the LCs are occupied. In such a case, the PU blocking probability, $P^2_{block,p}$, can be written as follows

$$P^2_{block,p} = \sum_{k=0}^{C_2} \sum_{l=0}^{C_2-k} p_{C_1,0,k,l}$$

3.7.3.2 SU dropping probability

The dropping probability can be expressed as the total SU dropping rate divided by the total SU connection rate. Therefore, the SU dropping probability is given as follows

$$P^2_{drop,s} = \frac{\sum_{i=0}^{C_1-1} \sum_{j=0}^{C_2} \lambda_1 p_{i,C_1-i,C_2-j.j}}{\left(1 - P^2_{block,s}\right) \lambda_2} \tag{3.12}$$

3.7.3.3 SU successful transmission probability

An SU has a successful transmission if the following two conditions happen:

- There are free channels for the SUs upon the moment of their arrival i.e. there is no block AND
- The arrival of PUs does not affect the SUs performance, i.e. there is no drop

Thus, the SU transmission probability, P_{succ}, can be easily calculated as follows:

$$P_{succ} = 1 - P^2_{block,s} - P^2_{drop,s} \tag{3.13}$$

3.7.3.4 SUs throughput

The SUs throughput, T_s^2 can be defined as the product of connection completion rate, $\left(1 - P^2_{block,s}\right)\left(1 - P^2_{drop,s}\right)\lambda_2$ and the average duration of the successfully completed connections, $\left(\frac{\mu_2}{1-P^2_{drop,s}}\right)^{-1}$. Thus, the SUs throughput T_s^2 can be written as follows

$$T_s^2 = \left(1 - P^2_{block,s}\right)\left(1 - P^2_{drop,s}\right)^2 \rho_2 \tag{3.14}$$

where $\rho_2 = \frac{\lambda_2}{\mu_2}$.

3.7.3.5 SU spectrum handoff process

The OSAB spectrum handoffs process [79] is different from other spectrum handoffs process presented in Section 3.4. In OSAB, the selection of a target channel, to perform a spectrum handoff, depends completely on the spectrum availability on LCs and UCs not on LCs only. Moreover, each type of channels (i.e. LCs and UCs) has its own characteristics. If the target channel is a LC, there is a probability to perform another handoff since PUs have a highest priority to access those channels. If the target channel is a UC, no more spectrum handoffs is needed since UCs are free from PUs. For that reason, calculating SU spectrum handoff probability is a complicated mathematical problem. For accurate mathematical derivation of the spectrum handoff probability, we present the following steps:

- Firstly, we calculate the handoff requirement probability which is the probability that a PU arrives and selects the channel occupied by an SU,
- Secondly, we calculate the link maintenance probability which is the probability that the SU link is either successful or failed after a PU appears (the link can be maintained on LCs or UCs),

- Finally, from the aforementioned probabilities, we derive a form for the spectrum handoff probability and thus the SU expected number of spectrum handoffs can be calculated.

Handoff requirement probability

During the SU service, a PU may appear and reclaim this channel. After the channel release, the SU will perform the link maintenance to re-construct the communications in order to avoid service termination. During this procedure, the SU searches for a new channel from LCs or UCs to transfer its communications, if available. In such a case, the SU performs a spectrum handoff. The handoff requirement probability P_H of the SU from a given LC is the probability that the PU arrives and selects the channel occupied by an SU. That is,

$$P_H = \frac{\lambda_1}{1 - P^2_{block,p}} \times \sum_{i=1}^{C_1} \sum_{j=0}^{C_1-i} \sum_{k=0}^{C_2} \sum_{l=0}^{C_2-k} \frac{j}{C_1 - i} p_{i,j,k,l}$$

Let P_{NH} denotes the probability that an SU need not vacate its channel i.e., the probability that PU arrives and occupies a channel different from the one used by the SU. Thus, P_{NH} can be given as follows

$$P_{NH} = \frac{\lambda_1}{1 - P^2_{block,p}} \times \sum_{i=1}^{C_1} \sum_{j=0}^{C_1-i} \sum_{k=0}^{C_2} \sum_{l=0}^{C_2-k} \left(1 - \frac{j}{C_1 - i}\right) p_{i,j,k,l}$$

Link maintenance probability

In each a spectrum handoff, the link maintenance may be either successful or fail. Let L_f denotes the probability that the SU vacates the channel and the spectrum handoff failed. This probability is equal to the probability that a PU appears and there are no free channels either on LCs or UCs.

$$L_f = P_H P^2_{block,s}$$

Let L_{UC} denotes the probability that a link is successfully maintained on a channel from UCs when the SU abandoned the channel. In such a case, the link maintenance probability L_{UC} can be written as follows

$$L_{UC} = P_H \times \sum_{i=1}^{C_1} \sum_{j=0}^{C_1-i} \sum_{k=0}^{C_2} \sum_{l=0}^{C_2-k} p_{i,j,k,l}$$

Let L_{LC} denotes the probability that link is successfully maintained on an LC when the SU abandoned the channel. In such a case, the link maintenance probability L_{LC} can be written as follows

$$L_{LC} = P_H \times \sum_{i=1}^{C_1} \sum_{j=0}^{C_1-i} \sum_{k=0}^{C_2} p_{i,j,k,c_2-k}$$

Spectrum handoff probability

In order to appropriately characterize performance metrics such as spectrum handoff probability, it is therefore necessary to have an appropriate distribution model for the SU service time to reflect the spectrum mobility of the users. Laplace transform is such a model. Laplace transform is used to convert time domain relationships to a set of equations expressed in terms of the Laplace operator s. Thereafter, the solution of the original problem is effected by simple algebraic manipulations in the, s, or Laplace domain rather than the time domain.

In this section, we will apply Laplace transform to derive the spectrum handoff probability and the expected number of spectrum handoffs for SUs. To reach our goal, we assume the following:

- Let I_{P_i} be a random variable (RV) denoting the PU inter-arrival time between $(i-1)$th and ith PU with the generic form I_P. Here, the first PU refers to the immediate next PU after an SU admits the system. Let $\Phi_k = \sum_{i=1}^{k} I_{P_i}$. For Poisson PU arrival process, Φ_k follows an Erlang distribution with the pdf $f_{\Phi_k}(t)$ given as [80, p.376]

$$f_{\Phi_k}(t) = \frac{\lambda_1 (\lambda_1 t)^{k-1}}{(k-1)!} e^{-\lambda_1 t}$$

- Let T_s be the service time of a SU with expectation $\frac{1}{\mu_2}$, pdf $f_{T_s}(t)$, Laplace transform $f_{T_s}^*(s)$, CDF $F_{T_s}(t) = \int_{\tau=0}^{t} f_{T_s}(\tau)\, d\tau$, Complementary CDF $\overline{F_{T_s}}(t) = 1 - F_{T_s}(t)$ and Laplace transform $F_{T_s}^*(t)$.

Let us concentrate on a particular SU called *tagged SU*. Let H be a RV denoting the number of spectrum handoffs for the *tagged SU* from the moment the transmission started till the transmission ended or the *tagged SU* forcedly terminated. When the *tagged SU* vacates the operating data channel, where the SU transmission started, it will continue its transmission in a BC if there is at least one free channel. Otherwise, it will handoff from a channel to another channel till its transmission finishes. Let us concentrate on the PUs that arrive at the system after the *tagged SU* admitted in the system. The spectrum handoff probability can be calculated according to the following two possibilities: zero spectrum handoff (i.e., $k = 0$) or $k \geq 1$ spectrum handoffs.

First, the *tagged SU* will make zero spectrum handoffs until it completes its transmission if one of the following two cases happens:

1. *Case 1*: the service time of the *tagged SU* is less than the PU inter-arrival time i.e. $T_s < I_p$.

2. *Case 2*: there are several PUs arriving during the service time of the *tagged SU i.e.* $\Phi_k < T_s < \Phi_{k+1}$ and these PUs use different channels with probability P_{NH}. In such case, the *tagged SU* is not affected by PUs arrival and therefore it's not necessary that the *tagged SU* vacates the channel for performing a spectrum handoff.

From the aforementioned cases, the probability of zero handoff $P[H=0]$ is given as follows

$$\begin{aligned}
&P[H=0] \\
=\ & \Pr[T_s < I_p] + \sum_{k=1}^{\infty} \Pr[\Phi_k < T_s < \Phi_{k+1}] P_{NH}^k \\
=\ & \int_{t=0}^{\infty}\int_{\tau=t}^{\infty} f_{T_s}(t)\lambda_1 e^{-\lambda_1\tau} d\tau dt + \sum_{k=1}^{\infty}\int_{t=0}^{\infty} f_{T_s}(t) \Pr[\Phi_k < t < \Phi_{k+1}] P_{NH}^k
\end{aligned}$$

$$\begin{aligned}
&= f_{T_s}^*(\lambda_1) + \int_{t=0}^{\infty} f_{T_s}(t) e^{-\lambda_1 t}\left(e^{\lambda_1 t P_{NH}} - 1\right) dt \\
&= f_{T_s}^*(\lambda_1) + \int_{t=0}^{\infty} f_{T_s}(t) e^{-\lambda_1(1-P_{NH})t} dt - \int_{t=0}^{\infty} f_{T_s}(t) e^{-\lambda_1 t} dt \\
&= f_{T_s}^*(\lambda_1) + f_{T_s}^*(\lambda_1(1-P_{NH})) - f_{T_s}^*(\lambda_1) \\
&= f_{T_s}^*(\lambda_1(1-P_{NH}))
\end{aligned}$$

Second, the *tagged SU* will make $k \geq 1$ handoffs until it completes its transmission or is forcedly terminated. We consider the following three cases:

1. *Case 1*: the *tagged SU* makes $k-1$ handoffs on the LCs and then succeeds to access the UC in the kth handoff (i.e., the *tagged SU* fails to access the UCs $k-1$ times). In such a case, the *tagged SU* will complete its transmission in that channel without interruption.

2. *Case 2*: the *tagged SU* makes k handoffs on the LCs until completing its transmission (i.e., the *tagged SU* fails to access the UCs k times).

3. *Case 3*: the *tagged SU* is forcedly terminated in the kth handoff (i. e., the *tagged SU* fails to access the LCs or the UCs in the kth handoff).

Let P_k^{UC}, P_k^{LC} and P_k^{T} denote the probabilities for *Case 1*, *Case 2* and *Case 3*, respectively. Then, the probability for k handoffs until the *tagged SU* completes its transmission or is forcedly terminated, is given as

$$\Pr[H=k] = \Pr\left[P_k^{UC}\right] + \Pr\left[P_k^{LC}\right] + \Pr\left[P_k^{T}\right] \quad (3.15)$$

Calculating P_k^{UC}

The probability P_k^{UC} includes the following possibilities. There are $k+j$ PUs arrive to the system during the transmission time of the *tagged SU*. Among these PU arrivals, k PUs requests the same channel used by the *tagged SU* and the other j PUs arrivals join different channels with probability P_{NH}^j. The *tagged SU* checks UCs firstly to perform the spectrum handoff process. If one of the UCs is free and the link is maintained successfully with probability L_{UC}, the *tagged SU* performs spectrum handoff to this channel and continues its transmission in that channel without interruption. The *tagged SU* performs such spectrum handoff even if there are free LCs. If there is no free UCs, the *tagged SU* performs $(k-1)$ spectrum handoff to one of the free LCs with probability L_{LC}^{k-1}. Then the value of the $\Pr\left[P_k^{UC}\right]$ can be obtained as follows.

$$\Pr\left[P_k^{UC}\right] = \sum_{j=0}^{\infty} \Pr\left[T_s > \Phi_{k+j}\right] \begin{pmatrix} k+j-1 \\ j \end{pmatrix} L_{LC}^{k-1} P_{NH}^j L_{UC}$$

After some mathematical manipulations,

$$\Pr\left[P_k^{UC}\right] = \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_{UC}}{(k-1)!} \overline{F}_{T_s}^{*(k-1)} \left(\lambda_1 \left(1-P_{NH}\right)\right) \tag{3.16}$$

where $\overline{F}_{T_s}^{*(k-1)}$ denotes the derivative of $(k-1)$th order.

Calculating P_k^{LC}

The probability P_k^{LC} includes the following possibilities. There are $k+j$ PUs arrive at the system during the transmission time of the *tagged SU*. Among these PU arrivals, k PUs requests the same channel used by the *tagged SU* and the other j PUs arrivals join different channels with probability P_{NH}^j. The *tagged SU* will maintain the connection on the LCs k times with probability L_{LC}^k. Then the value of the $\Pr\left[P_k^{LC}\right]$ can be obtained as follows.

$$\Pr\left[P_k^{LC}\right] = \sum_{j=0}^{\infty} \Pr\left[\Phi_{k+j} < T_s < \Phi_{k+j+1}\right] \begin{pmatrix} k+j \\ j \end{pmatrix} L_{LC}^k P_{NH}^j$$

After some mathematical manipulations,

$$\Pr\left[P_k^{LC}\right] = \frac{\left(-\lambda_1 L_{LC}\right)^k}{k!} f_{T_s}^{*(k)} \left(\lambda_1 \left(1-P_{NH}\right)\right) \tag{3.17}$$

Calculating P_k^T

The probability P_k^T includes the following possibilities. There are $k+j$ PUs arrive at the system during the transmission time of the *tagged SU*. Among these PU arrivals, k PUs requests the same channel used by the *tagged SU* and the other j PUs arrivals join different channels with probability P_{NH}^{j}. On the other hand, the transmission time of the *tagged SU* is greater than PU inter-arrival i.e $T_s > \Phi_{k+j}$ and fails to access the LCs or the UCs in the $(k+1)$th handoffs. Then the value of the $\Pr\left[P_k^T\right]$ can be obtained as follows.

$$\Pr\left[P_k^T\right] = \sum_{j=0}^{\infty} \Pr\left[T_s > \Phi_{k+j}\right] \begin{pmatrix} k+j-1 \\ j \end{pmatrix} L_{LC}^{k-1} P_{NH}^{j} L_f$$

After some mathematical manipulations, we get

$$\Pr\left[P_k^T\right] = \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_f}{(k-1)!} \overline{F}_{T_s}^{*(k-1)}\left(\lambda_1\left(1-P_{NH}\right)\right) \tag{3.18}$$

The detailed mathematical derivation for P_k^{UC}, P_k^{LC} and P_k^T is described in Appendix A. Substituting from (3.16)-(3.18) in (3.15), we get

$$\begin{aligned}
\Pr\left[H=k\right] &= \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_{UC}}{(k-1)!} \overline{F}_{T_s}^{*(k-1)}\left(\lambda_1\left(1-P_{NH}\right)\right) \\
&\quad + \frac{\left(-\lambda_1 L_{LC}\right)^{k}}{k!} f_{T_s}^{*(k)}\left(\lambda_1\left(1-P_{NH}\right)\right) \\
&\quad + \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_f}{(k-1)!} \overline{F}_{T_s}^{*(k-1)}\left(\lambda_1\left(1-P_{NH}\right)\right) \\
&= \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 \left(L_{UC}+L_f\right)}{(k-1)!} \overline{F}_{T_s}^{*(k-1)}\left(\lambda_1\left(1-P_{NH}\right)\right) \\
&\quad + \frac{\left(-\lambda_1 L_{LC}\right)^{k}}{k!} f_{T_s}^{*(k)}\left(\lambda_1\left(1-P_{NH}\right)\right)
\end{aligned}$$

Average number of spectrum handoffs

The average number of spectrum handoffs until the SU completes or terminates its transmission, can be obtained as follows:

$$\begin{aligned}
E\left[H\right] &= \sum\nolimits_{k=1}^{\infty} k \Pr\left[H=k\right] \\
&= \sum\nolimits_{k=1}^{\infty} k \Pr\left[P_k^{UC}\right] + \sum\nolimits_{k=1}^{\infty} k \Pr\left[P_k^{LC}\right] + \sum\nolimits_{k=1}^{\infty} k \Pr\left[P_k^{T}\right] \\
&= \sum\nolimits_{k=1}^{\infty} k \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 \left(L_{UC}+L_f\right)}{(k-1)!} \overline{F}_{T_s}^{*(k-1)}\left(\lambda_1\left(1-P_{NH}\right)\right) \\
&\quad + \sum\nolimits_{k=1}^{\infty} k \frac{\left(-\lambda_1 L_{LC}\right)^{k}}{k!} f_{T_s}^{*(k)}\left(\lambda_1\left(1-P_{NH}\right)\right)
\end{aligned}$$

After straightforward calculation we obtain

$$E[H] = \frac{\lambda_1 (L_{UC} + L_f)[\Psi + \lambda_1 L_{LC}]\left(1 - f^*_{T_s}(\lambda_1 \Psi)\right)}{\Psi^2} + \frac{\lambda_1 L_{UC}[\lambda_1 (L_{UC} + L_f) - \Psi] f^{*(1)}_{T_s}(\lambda_1 \Psi)}{\Psi}$$

where $\Psi = 1 - P_{NH} - L_{LC}$.

3.7.3.6 SU effective transmission time

The arrival of PUs during SU's transmission increases the effective transmission time for such SU. When a PU arrives, the SU switches initially to a BC from UCs. If there is no free UCs, the channel with the least PU's activity from LCs is selected as a BC. In such a case, the communication session for the SU is disrupted for a short period of time which is equal to the switching time, T_{Switch}. If there is no free channel from LCs or UCs, a new negotiation is started between the transmitter and receiver like OSA, which maximizes the interruption duration for SUs utilizing OSAB. Thus, the interruption duration in such a case, T_{OSAB}, can be given as follows

$$T_{OSAB} = \begin{cases} T_{Switch}, & \text{if there is a BC} \\ T_{Sense} + T_{Neg} + T_{Dec} + T_{Switch} & \text{Otherwise} \end{cases}$$

where T_{Sense}, T_{Neg}, T_{Dec} and T_{Switch} are the periods of time needed for spectrum sensing, spectrum negotiation between the transmitter and the receiver, spectrum decision and spectrum switching, respectively. In the contrary, the communication session for the SUs using OSA's spectrum handoff, is disrupted always for a long period of time. The interruption duration for OSA, T_{OSA}, can be given as follows

$$T_{OSA} = T_{Sense} + T_{Neg} + T_{Dec} + T_{Switch}$$

The *tagged SU*'s effective transmission time T_{eff} is defined as the time between the instant when the *tagged SU* begins its transmission to the instant when it ends its transmission. The value of T_{eff} can be calculated as follows:

1. the service time of the *tagged SU* if there is no interruption from PUs OR
2. The product of the number of spectrum handoffs and the SU's service time of the *tagged SU* plus the switching time, T_{Switch}. We assume that once the *tagged SU* is interrupted by a PU, it start its transmission again (i.e. there is no resume for the transmission).

Thus, T_{eff} is given as follows

$$T_{eff} = T_s + E[H][T_{Switch} + T_s] \tag{3.19}$$

3.8 Numerical results

In this section, a comparison between OSA and OSAB is presented in terms of the following performance metrics for SUs: blocking probability, dropping probability, throughput, successful transmission probability, the expected number of spectrum handoffs and effective transmission time. We consider three different scenarios to evaluate the performance of both models.

3.8.1 Scenario 1: Opportunistic spectrum access with same number of channels and exclusive UCs

In this scenario, we evaluate OSA and OSAB using the same number of channels (i.e. $C = C_1 + C_2 = 6$). However, different types of channels are utilized by each model. Since OSA is managing the available spectrum over LCs only and neglecting the existence of UCs, we set $C_1 = 6$ and $C_2 = 0$. For OSAB, we set C_1, and C_2, to be 4 and 2, respectively. Moreover, the two UCs are reserved exclusively to SUs (i.e. no CUs traffic loads on UCs). Figure 3.7 plots different performance metrics for scenario 1 as a function of PU arrival rate, λ_1. The basic parameters for this scenario are configured as: $0 < \lambda_1 \leq 0.8$, $\mu_1 = 0.1$ or $0.2, \lambda_2 = 0.25$, $\mu_2 = 0.2$, $\lambda_3 = 0$ and $\mu_3 = 0$.

SU blocking probability: The SU blocking probability is defined as the probability that all the channels in a service area are occupied by either PU and/or SU and no channel is available for a new SU request. Figure 3.7-a depicts the blocking probabilities for both OSA and OSAB models. As can be seen, the SU blocking probabilities for both models increase with increasing the value of λ_1. This can be explained as follows: As λ_1 increases, the number of LCs that can be accessed opportunistically by the SUs reduces, which leads to a high blocking probability for SUs. However, OSAB decreases the blocking probability compared to OSA by 44.02%. This is intuitively clear for the following two reasons: 1) OSAB utilizes the UCs exclusively and 2) the service rate for SUs is twice the service rate for PUs (i.e. $\mu_2 = 2\mu_1 = 0.2$). A smaller value of μ_1 implies a longer service time for PUs which causes the probability that all LCs are occupied to increase and thus increases $P^1_{block,s}$. With OSAB, μ_1 has no impact on the two UCs and the time needed to serve SUs is low which increases the availability of the two UCs and thus decreases $P^2_{block,s}$. Figure 3.7-b illustrates $P^1_{block,s}$ and $P^2_{block,s}$ with the same service rate for PUs and SUs (i.e. $\mu_2 = \mu_1 = 0.2$). As expected, the blocking probabilities for both models are decreased compared to the results obtained from Figure 3.7-a. This is clear since the time needed to serve PUs is reduced which increases the chance for SUs to utilize one of LCs and thus decrease the blocking probability. In this figure, OSAB decreases the blocking probability compared to OSA by 24.39%.

SU dropping probability: In Figures 3.7-c and d, the dropping probability for the classical OSA model, $P^1_{drop,s}$, is high compared to the one obtained from

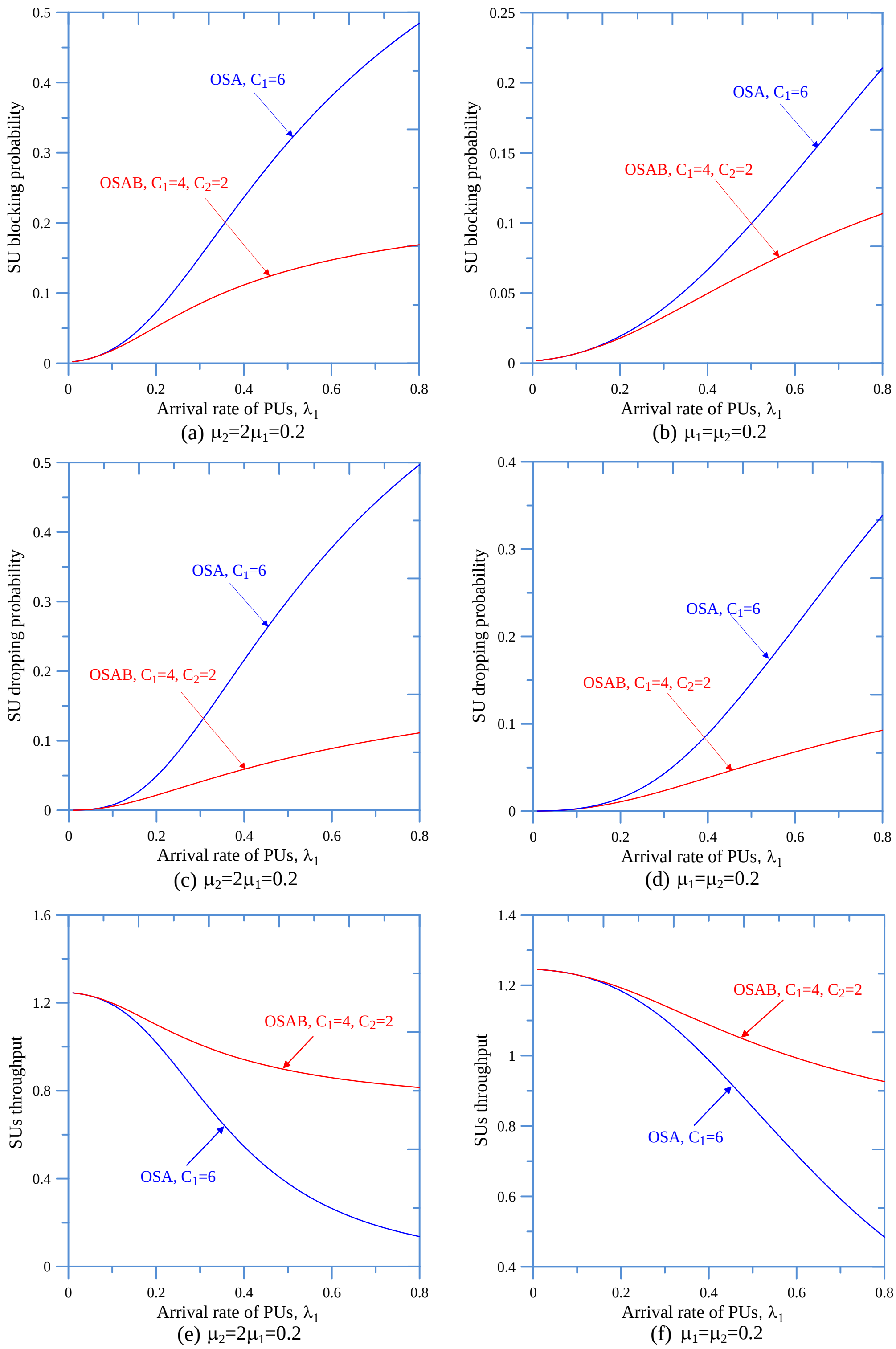


Figure 3.7: Performance metrics for scenario 1 as a function of PU arrival rate, λ_1 and $\lambda_2 = 0.25$, $\lambda_3 = 0$, $\mu_3 = 0$ (a)-(b) SU blocking probability, (c)-(d) SU dropping probability and (e)-(f) throughput

the OSAB model, $P^2_{drop,s}$. The difference between the dropping probabilities for both models can be clarified as follows: In OSA model, as the arrival rate of PUs increases, the SUs are forced to vacate this channel and search for a new channel. This process continues till all LCs are occupied and hence the dropping probability for SU increases. In OSAB, when the arrival rate of PUs increases, the SUs perform spectrum handoffs to a channel from the UCs. Since UCs are free from PUs and are utilized exclusively by SUs, the SUs will continues their transmission without any interruption. From Figure 3.7-c, OSAB decreases the dropping probability compared to OSA by 61.79%. Obviously, increasing the service rate for PUs has no significant impact on the SU dropping probability since the dropping probability is affected by PUs arrival rate only.

SUs throughput: Figures 3.7-e and f depict the throughput for OSA and OSAB models as a function of λ_1 and different service rates for PUs. The throughput (see equations 3.7 and 3.14) is calculated as the number of successful SUs transmission per unit time. This number depends completely on both blocking and dropping probabilities of SUs. Thus, it is intuitive that with low values for both probabilities, the throughput increases. This explains why at low PU arrival rate, the SUs throughput increases. With λ_1 increases, the throughput for both models decrease. This reduction is a result of increasing blocking and dropping probabilities in both models. However, OSAB increases the SUs throughput compared to OSA by 78.54% on average. This enhancement is a result of using two exclusive UCs.

3.8.2 Scenario 2: Opportunistic spectrum access with same number of channels and shared UCs

In this scenario, both models utilize the same number of channels as same as scenario 1. However, the UCs are shared between SUs and CUs. Furthermore, we evaluate this scenario with different CUs arrival rates (i.e., $\lambda_3 = 0.1$, $\lambda_3 = 0.25$ and $\lambda_3 = 0.5$) and fixed service rate (i.e., $\mu_3 = 0.2$) on the two UCs. Figures 3.8 and 3.9 plot different performance metrics for scenario 2 as a function of PU arrival rate, λ_1.

SU blocking probability: Figure 3.8-a plots the effect of CUs arrival rates (i.e., λ_3) with fixed service rate (i.e., $\mu_3 = 0.2$), on the SU blocking probability. Following a similar argument like scenario 1, the blocking probabilities for both models increase as λ_1 increases. However, the SU blocking probability in OSAB behaves differently compared to the one obtained from Figure 3.7-a. Obviously, increasing CUs arrival rate leads to minimizing the number of UCs that can be accessed by the SUs. Thus, the SU blocking probability increases as a result of reducing the number of UCs. To study the effects of the service rate of PUs, μ_1 on the blocking probability, we increase the service rate of PUs (i.e., low service time for PUs). As plotted in Figure 3.8-b, increasing μ_1 leads to decreasing the blocking probability of SUs, compared to the result obtained from Figure 3.8-a,

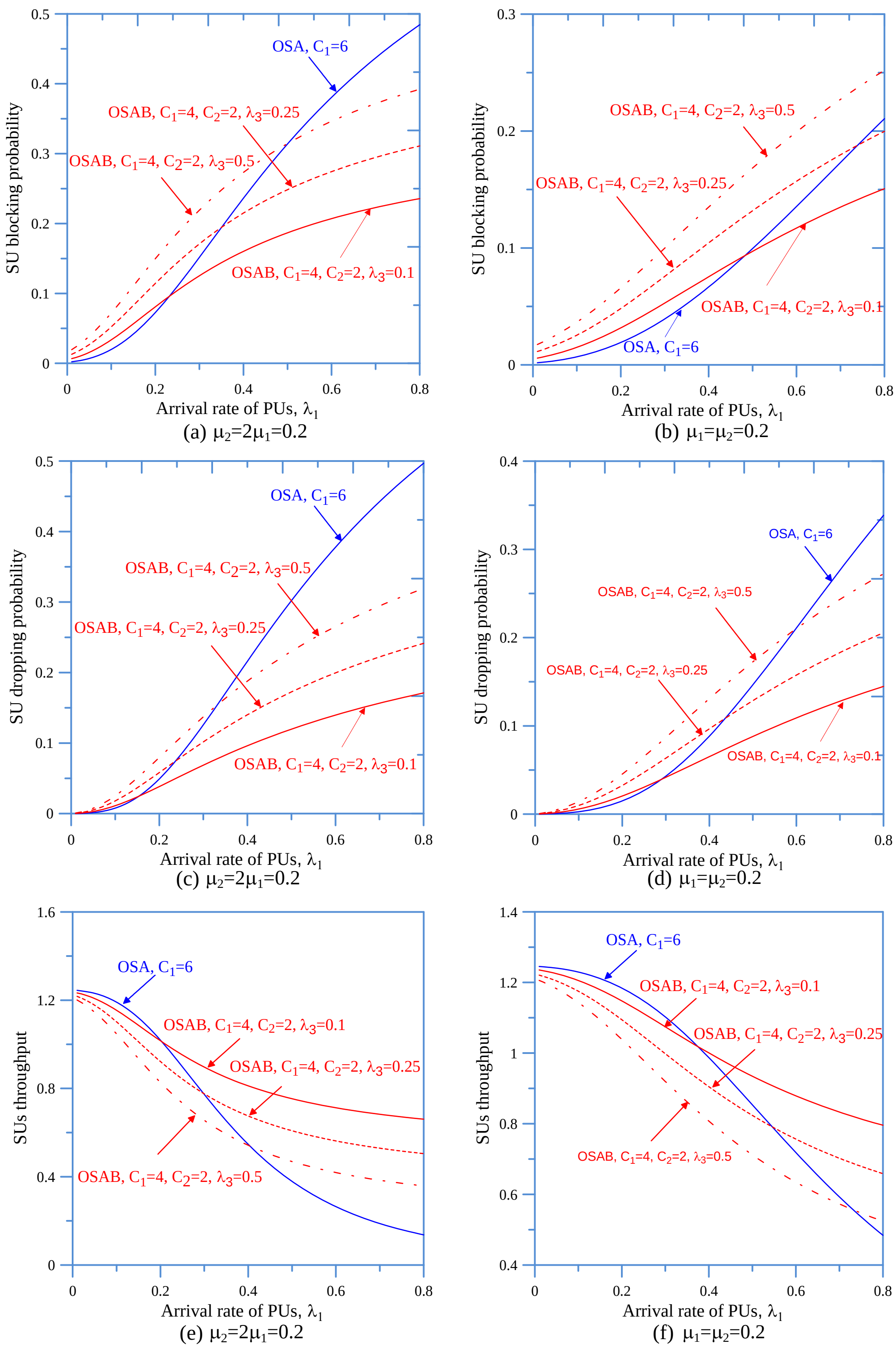


Figure 3.8: Performance metrics for scenario 2 as a function of PU arrival rate, λ_1 and $\lambda_2 = 0.25$, $\mu_3 = 0.2$ (a)-(b) SU blocking probability, (c)-(d) SU dropping probability and (e)-(f) throughput

since more LCs are available.

SU dropping probability: Figures 3.8-c and d show the effect of CUs arrival rates (i.e. λ_3) with fixed service rate (i.e., $\mu_3 = 0.2$), on the SU dropping probability. The results, obtained from this figure, can be explained as follows: In OSAB, with different values of λ_3 and low PU arrival rate , the number of channels, accessed by SUs on OSAB, reduce compared to OSA which utilizes 6 LCs at low PUs arrival rate. Thus the SU dropping probability increases compared to OSA. At high PU arrival rate, the number of channels, accessed by SUs on both models, minimizes. However, the results obtained for OSAB outperform the one obtained for OSA since the two UCs is still accessible by SUs on OSAB (UCs are shared between SUs and CUs with equal priorities).

SU throughput: Figures 3.8-e and f illustrate the SUs throughput with different values of λ_3 and fixed service rate on UCs. Obviously, increasing λ_3 and using fixed service rate (i.e., $\mu_3 = 0.2$) on UCs leads to reducing the number of UCs that can be accessed by SUs and thus the throughput for OSAB decreases compared to OSA. The reduction on the SU throughput is a normal result for the increase on the blocking and dropping probabilities as seen in Figures 3.8 a, b, c and d.

SU successful transmission probability: Figures 3.9-a and b show, P_{succ}, in terms of PU arrival rate, λ_1 for both OSAB and OSA. P_{succ} depends completely on SUs blocking and dropping probabilities (note: $P_{succ} = 1 - P^2_{block,s} - P^2_{drop,s}$). Obviously, when both values increase, P_{succ} decreases. The results obtained from these figures are straightforward calculations from the ones obtained in 3.8-a, b, c and d.

SU expected number of spectrum handoffs: Figure 3.9-c presents a comparison between OSA and OSAB in term of the expected number of spectrum handoffs, $E[H]$, that SUs perform to finish its transmission. As expected the number of spectrum handoffs for both models increases as λ_1 increases. However, each model behaves differently. The results obtained from this figure can be described as follows: At low PUs arrival rate: since we assume that SUs operate on LCs firstly and the number of LCs is different in each model (OSA uses 6 LCs and OSAB uses 4 LCs), the probability that a PU preempts an SU increases in OSAB compared to OSA. This implies that SUs perform more spectrum handoffs to maintain their links. At high PUs arrival rate: the appearance of PUs affects greatly both models and increases the number of spectrum handoffs. It is clear that, increasing λ_3 and using a fixed service rate (i.e., $\mu_3 = 0.2$) on UCs increases the number of spectrum handoffs. At low CUs arrival rate, the probability for accessing one of UCs, is high and thus no more spectrum handoffs is needed. At high CUs arrival rate, the probability to access a channel from UCs decreases since there is a competition between SUs and CUs to access the UCs.

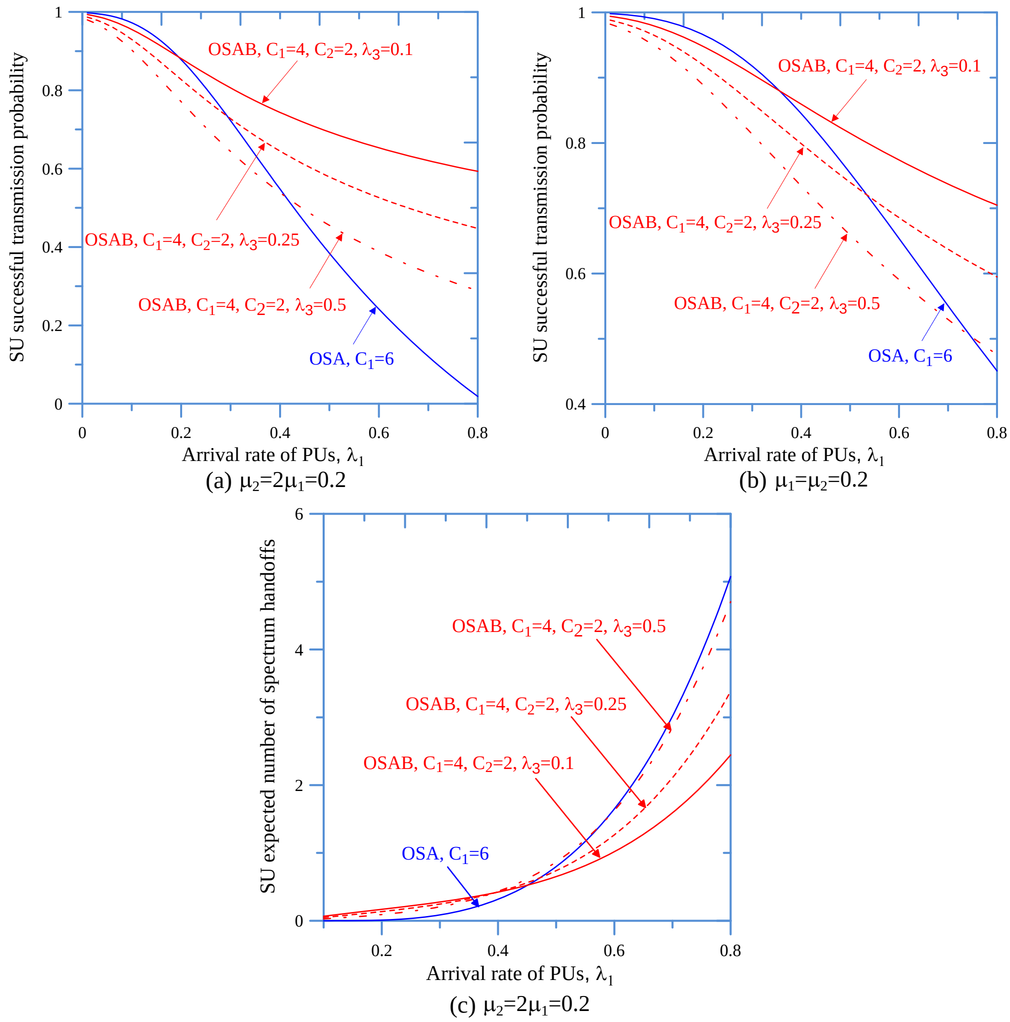


Figure 3.9: Performance metrics for scenario 2 as a function of PU arrival rate, λ_1 and $\lambda_2 = 0.25$, $\mu_3 = 0.2$ (a)-(b) SU successful transmission probability, (c) SU expected number of spectrum handoffs

3.8.3 Scenario 3: Opportunistic spectrum access with same number of LCs and shared UCs

In this scenario, both OSA and OSAB utilize the same number of LCs (i.e. $C_1 = 6$). In addition, OSAB is not neglecting the existence of UCs like OSA. Thus, we assume the existence of two additional UCs on OSAB. One may argue that adding additional resources leads intuitively to enhance the performance of SUs in terms of blocking probability, dropping probability, etc. For such a reason, we saturate the two UCs by CU traffic loads. We expect from this study that, even if the two UCs is saturated, a combination of LCs and UCs is a better spectrum management approach. Figures 3.10 and 3.11 plot different performance metrics for scenario 3 as a function of PU arrival rate, λ_1. The basic parameters for this scenario are configured as the ones used in scenario 2.

SU blocking probability: Figures 3.10-a and b depict the SU blocking probability as a function of λ_1. For each of the two figures we also show the impact of different CU arrival rates. Intuitively, increasing the PU arrival rate leads to increase the SU blocking probability for both OSA and OSAB. However, OSAB decreases the SU blocking probability compared to OSA by 40.7% even if the CUs arrival rate is high (i.e. $\lambda_3 = 0.5$). Clearly, increasing the SU service rate, as shown in Figure 3.10-b, results on decreasing the blocking probabilities for both models compared to the results obtained from 3.10-a. We conclude from the previous study that: utilizing both LCs and UCs as spectrum environment for SUs, even if UCs are congested, is a better approach than utilizing LCs only.

SU dropping probability: Figures 3.10-c and d displays the SU dropping probability for both OSA and OSAB as a function of PU arrival rate, λ_1. Even if the CU arrival rate is high (i.e. $\lambda_3 = 0.5$), OSAB decreases the SU dropping probability compared to OSA by 45.7%. This result can be clarified as follows: both SUs and CUs have the same priority to access the two UCs. Thus, once the SU forced to vacate one of the LCs, it continues transmission on one of the UCs without interruption.

SU throughput: Figure 3.10-e and f shows the SU throughput for both models as a function of PU arrival rate. Since the SU throughput depends completely on both SU blocking and dropping probabilities, it is intuitively clear that decreasing the two probabilities causes an increase on the SUs throughput. Thus, OSAB increases the throughput compared to OSA by 76.59% even if the CUs arrival rate is high.

SU successful transmission probability: Figures 3.11-a and b show P_{succ} for the SUs with the variation of the arrival rate λ_1 and for high traffic load for the CUs. As expected, the OSAB concept increases P_{succ} compared to OSA by 90.5%.

SU expected number of spectrum handoff: Figure 3.11-c shows the expected number of spectrum handoff for the SUs with the variation of the arrival rate λ_1. Interestingly, the result show that, even if the CUs arrival rate is high in the two UCs, OSAB decreases $E\left[H\right]$ compared to OSA by 39.88%. This leads to an important conclusion, which is, neglecting the existence of UCs when performing a spectrum handoff, degrades the SU performance and also wastes network resources.

SU effective transmission time: Figure 3.11-d depicts the effective transmission time for SUs in OSA and OSAB. The effective transmission time is a function on the expected number of spectrum handoffs, see equation 3.19. As the expected number of spectrum handoff increases, the effective transmission time increases. Thus, the result obtained from Figure 3.11-d depends completely on the results obtained from Figure 3.11-c. Moreover, when the PU appears in a channel occupied by an SU, the interruption duration for this SU is equal to the switching time (T_{Switch}) only. In contrary, the communication session for

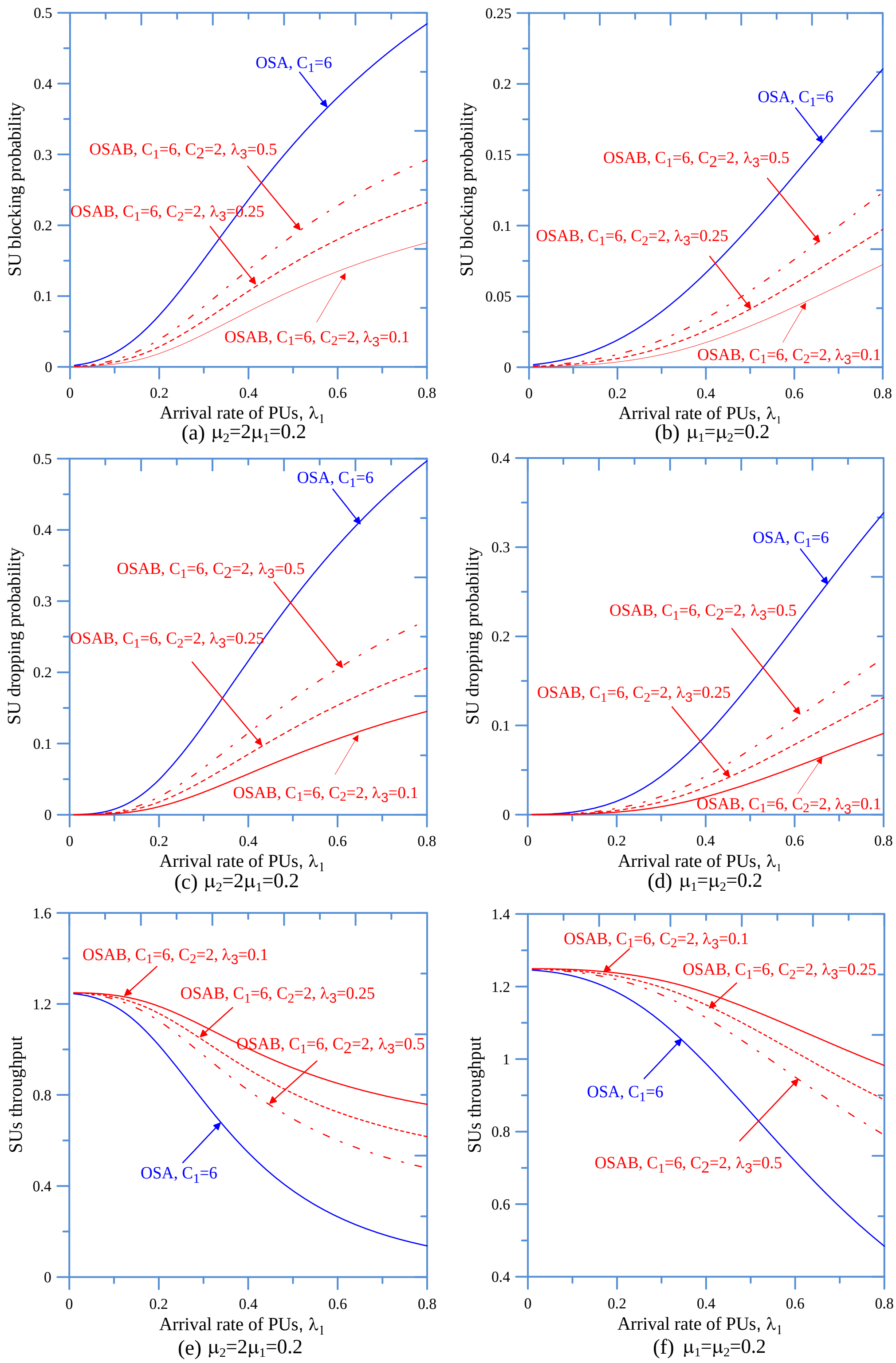


Figure 3.10: Performance metrics for scenario 3 as a function of PU arrival rate, λ_1 and $\lambda_2 = 0.25$, $\mu_3 = 0.2$ (a)-(b) SU blocking probability, (c)-(d) SU dropping probability and (e)-(f) throughput

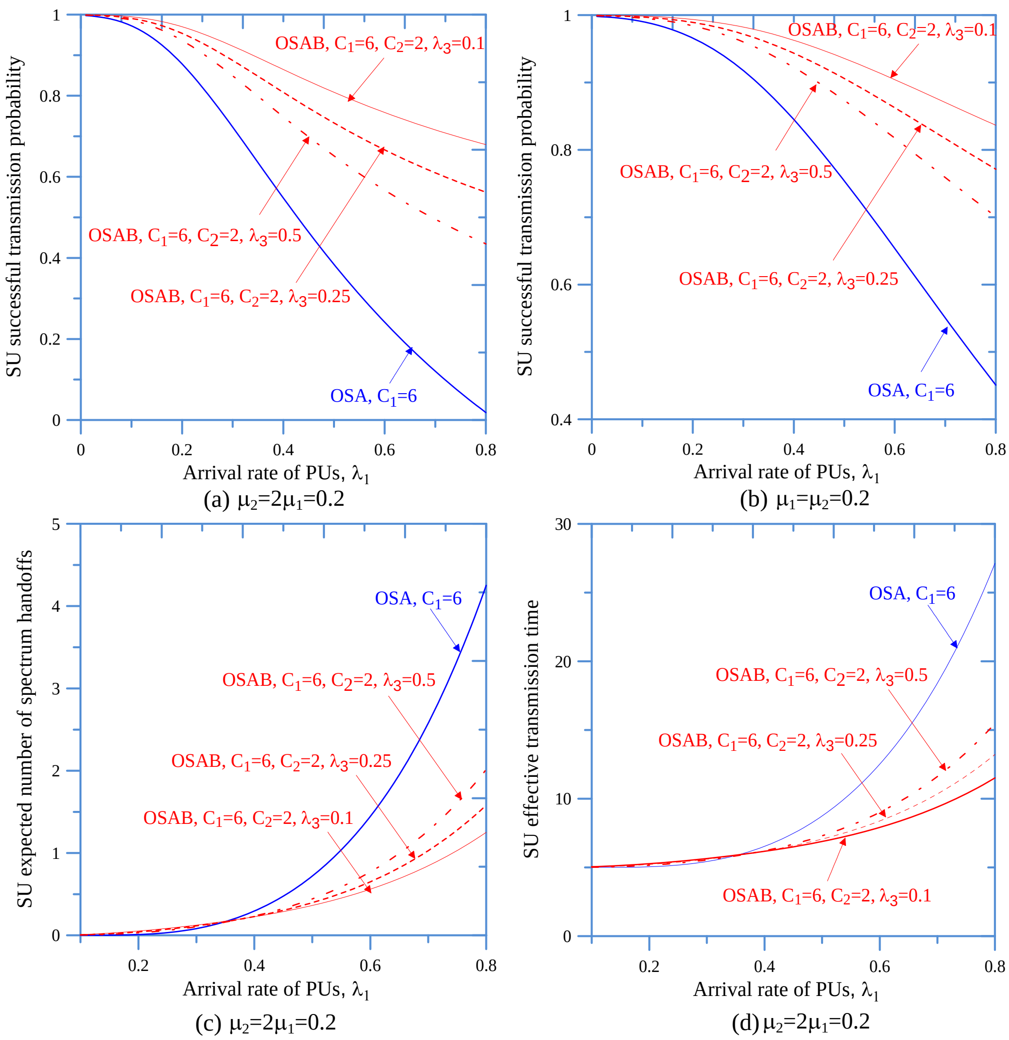


Figure 3.11: Performance metrics for scenario 3 as a function of PU arrival rate, λ_1 and $\lambda_2 = 0.25$, $\mu_3 = 0.2$ (a)-(b) SU successful transmission probability, (c) SU expected number of spectrum handoffs and (d) SU effective transmission time

the SUs using OSA's spectrum handoff, is disrupted always for a long period of time which is equal to the time needed for spectrum sensing, spectrum negotiation between the transmitter and the receiver, spectrum decision and spectrum switching, respectively. According to that the SUs effective transmission time in OSAB outperforms the one obtained from OSA. OSAB decreases the SU effective transmission time compared to OSA by 26.5% even if CU arrival rate is high.

Discussions

Despite the existence of more scenarios, we believe that the previously mentioned scenarios are adequate to measure the gain offered by the OSAB concept. It is important to mention that: In some situations, it is clear that OSAB outperforms OSA. This explains why some performance metrics, such as the effective transmission time, is not evaluated in scenario 1 and scenario 2. The general conclusion from the aforementioned results can be summarized as follows:

- Scenario 1: Although the results obtained from this scenario outperforms OSA results, this scenario requires changing the spectrum allocation policy from regulators since the UCs are used exclusively by SUs. Changing spectrum allocation policies is hard and needs time from regulators.
- Scenario 2: In this scenario, UCs are not used exclusively by SUs i.e., shared with other CUs. In addition, OSA utilizes more LCs compared to OSAB. Obviously, OSA outperforms OSAB in some cases especially when the CUs arrival rate is high.
- Scenario 3: This scenario is the most realistic scenario compared to scenarios 1 and 2. In this scenario, OSAB uses the same number of LCs used by OSA. However, OSAB manages and organizes the access to the available spectrum (i.e., LCs and UCs) efficiently. The results obtained from this scenario explain the negative impact of neglecting the existence of UCs on the OSA model. In addition, this scenario requires no effort to modify the spectrum allocation policy from regulators.

3.9 Chapter summary

The conclusion from this chapter can be listed as follows:

- This chapter has introduced a new spectrum management concept called OSAB. OSAB is a step toward eliminating the spectrum scarcity in today's ad hoc networks. It increases the spectrum capacity for ad hoc networks in addition to reducing the impact of the sudden appearance of PUs.
- OSAB uses a combination of channels from LCs and UCs as a spectrum environment for ad hoc devices instead of using channels from LCs only like other spectrum management concepts such as OSA. Thus, a better utilization of the available spectrum resources can be achieved.
- OSAB's spectrum handoff process is flexible to choose a channel from LCs or UCs in the case of PU appearance.
- Detailed Markov chain models are presented to evaluate the performance of SUs in both OSA and OSAB. The numerical results obtained from the Markov chain models prove that neglecting the existence of UCs has a negative impact on the SU performance in terms of different performance metrics. Thus, a combination of LCs and UCs, as a spectrum environment

for future ad hoc networks, is a more efficient approach compared to existing ones using LCs only.

- OSAB is an abstract concept; some open issues still exist such as: *How do SUs perform sensing?*, *How do SUs coordinate access to the available spectrum? How does the SU select the BC?* Thus, a detailed MAC protocol is needed to answer the aforementioned questions and to implement OSAB.

Chapter 4

SWITCH: An Opportunistic Spectrum Access WITh Backup CHannel MAC Protocol

In this chapter, a flexible multichannel MAC protocol, based on the OSAB concept, is developed. The new protocol is named opportunistic Spectrum access WITh backup CHannel (SWITCH) protocol. The performance of the proposed protocol is evaluated by simulation.

4.1 Introduction

Although various MAC protocols have been extensively studied in the context of classical ad hoc networks, they cannot be directly applied to CR ad hoc networks, which have some unique characteristics that clearly distinguish them from their classical counterparts. Firstly, the SUs should have the ability to seek adaptively and dynamically for opportunities in both licensed channels (LCs) and unlicensed channels (UCs). Secondly, the SUs should react efficiently to the sudden and the consecutive appearance of PUs.

These two characteristics make the design of an efficient CR-MAC protocol a challenge. In Chapter 2, we have given an extensive survey of CR-MAC protocols. According to this survey, CR-MAC protocols can be classified to: contention-based protocols, time slotted-based protocols and hybrid protocols. All of these protocols have pros and cons. However, the two aforementioned characteristics are not discussed in detail, especially the second one. The OSAB concept, presented in Chapter 3, is a solution for amending the two aforementioned challenges. To benefit from the OSAB concept, a flexible MAC protocol, that coordinates the access to the medium (LCs and UCs), should be developed. Therefore, the main goal of this chapter is introducing such a protocol. The proposed protocol is called opportunistic Spectrum access WITh backup CHannel (SWITCH) protocol. The SWITCH protocol is a decentralized, asynchronous, and connection-based MAC protocol for CR ad hoc networks. The proposed protocol operates over both LCs and UCs. In addition, the concept of BCs is introduced and employed to make the SU extremely robust to the appearance of PUs. The BC is negotiated between the transmitter and the receiver prior to an actual channel switch. Thus, it minimizes the coordination control overhead involved during the spectrum handoff process.

The remainder of this chapter is organized as follows. The proposed protocol is described in details in Section 4.2. The performance of the proposed protocol is evaluated by simulation in Section 4.3. Next, in Section 4.4, we present and discuss selected results from our analysis. In Section 4.5, we summarize the chapter.

4.2 SWITCH protocol

In this section, the proposed protocol is described in detail. Firstly, the design features are listed. Secondly, the assumptions are presented. Finally, the basic protocol operations are given.

4.2.1 Design features

The OSAB concept, proposed in Chapter 3, is a spectrum management concept for utilizing the available spectrum more efficiently. However, OSAB is an abstract concept and some open issues still exist such as: 1) *How does the transmitter/receiver pair coordinate access to the available spectrum?* 2) *How does the SU cope with the sudden appearance of PUs?* Thus, a detailed MAC protocol is needed to answer the aforementioned questions. This was a motivation for us to develop a new MAC protocol called SWITCH. SWITCH is proposed to implement the OSAB concept.

As discussed in Chapter 2, the SUs use a MAC protocol to coordinate the access to the available channels. CR-MAC protocols can be classified to: contention-based protocols, time slotted-based protocols and hybrid protocols. For amending the first issue mentioned above, SWITCH is a contention-based MAC protocol to coordinate access to the available channels. The selection of SWITCH to be a contention-based MAC protocol can be described as follows: time slotted and hybrid MAC protocols need synchronization among the nodes in the network which is quite a challenge in an environment that lacks a centralized entity. In addition, the MAC protocol operation must be adaptive to environmental changes (e.g. PU appearance), that makes applying synchronization a challenge. On the contrary, contention-based MAC protocols are asynchronous MAC protocols. This feature makes this class an appropriate candidate for designing a MAC protocol for CR ad hoc networks. In addition, this class utilizes a CCC as a rendezvous channel for the exchange of control packets for the whole network. Thus, all nodes in the network are aware of the spectrum availability in their vicinity. Obviously, increasing the number of nodes makes the CCC a bottleneck in the network. However, this problem can be easily solved by using a dynamic CCC or clustering the whole network and assigning each cluster one CCC. The End-to-End Reconfigurability (E2R) project [81] has shown that a CCC is very suited for CR networks. According to that, we have decided to develop a contention-based MAC protocol with some modifications which will be described later.

To handle the second issue, SWITCH uses the BC's conception proposed by OSAB. The BC is negotiated between the transmitter and the receiver prior to the actual data transmission. Thus, when a PU appears, both transmitter and receiver switch to the BC without additional control messages. This leads to minimizing the control overhead required to find a new channel in the case of PU's appearance. Furthermore, all nodes in the transmission range of both nodes are informed about such a switch and therefore, the number of data collisions is reduced.

4.2.2 Assumptions

SWITCH is developed using the following assumptions:

- Two types of channels are assumed: a CCC and data channels. The CCC is used as a rendezvous channel by SUs for (i) coordinating their access to the spectrum using control messages, and (ii) sharing and identifying spectrum opportunities gathered by different SUs. Two methods may be used for the assignment of the CCC:

    1. Static assignment: the CCC can be either specially licensed to the

SUs by the FCC or one of the UCs [82][83].

2. Dynamic assignment: the most reliable channel from the unoccupied (free) channels, which are licensed to PUs, is selected as CCC [84].

In this thesis, the selection of the CCC is not discussed and we assume that the CCC is statically assigned by the FCC. We assume also that the CCC is free from PUs.

The data channels are of two types: LCs and UCs. The maximum number of LCs and UCs are C_1 and C_2, respectively. The C_1 channels are used as operating channels in the case of PUs absence. The C_2 channels are used as BCs in the case of PUs appearance (Note: if there are no free channel from UCs, the channel with low PU activity is selected to be a BC).

- Each SU is equipped with two transceivers (TRx):

1. The first transceiver, TRx1, is devoted to operating over the CCC. The SUs use their TRx1 to obtain the information of the unused LCs and UCs, and to negotiate with the other SUs through contention based algorithms, such as IEEE 802.11 DCF,

2. The second transceiver, TRx2, consists of a Software Defined Radio (SDR) module. The SDR module can tune to any of the available channels, LCs and UCs, to sense for unused spectrum and moreover receive/transmit the SUs data. We assume that both transceivers coordinate with each other for collaboratively sensing and dynamically utilizing the available spectrum. Details about such coordination is given in Section 4.2.4. Although increasing the number of transceivers increases the hardware cost, we believe that using two transceivers is better than using one only. By using two transceivers, each node is empowered with the capability to use one of them to monitor the activity of other users (i.e., PUs, SUs and CUs) in its vicinity. Thus, data collisions can be reduced.

4.2.3 Cognitive cycle

To facilitate the description of the proposed protocol, we present a simplified cognition cycle for the SWITCH protocol in Figure 4.1. The four main functionalities for this cycle are spectrum sensing, spectrum allocation, spectrum sharing and spectrum mobility. The SWITCH cognition cycle is consistent with the generic cognition cycle presented in Chapter 2.

For spectrum sensing, SWITCH uses cooperative spectrum sensing by combining scanning results from neighboring nodes, and it implements a spectrum reservation scheme using a CCC. The scanning results are stored in the spectrum allocation data structure.

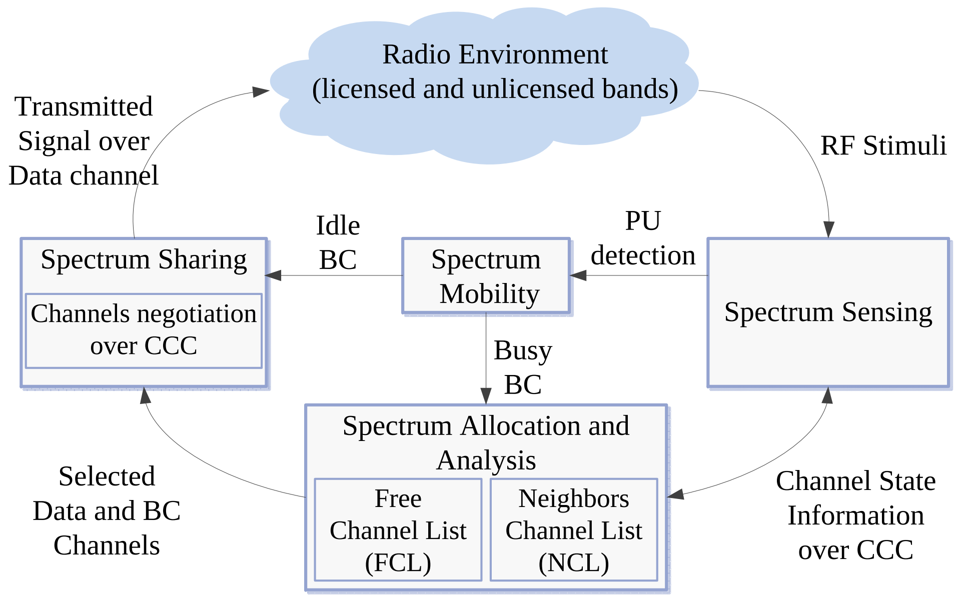


Figure 4.1: A simplified version of the cognition cycle for SWITCH

For spectrum allocation, the proposed protocol utilizes two spectrum allocation data structures, Neighbors Channel List (NCL), and Free Channel List (FCL). Details about these two lists are given in Section 4.2.5.

For spectrum sharing, when a node has packets to send, it first contends for access to the CCC using CSMA/CA and random backoff mechanisms of IEEE 802.11 presented in Chapter 2. The transmitter, upon winning access to the CCC, performs with its intended receiver a two-way handshake like IEEE 802.11 DCF or three-way handshake like the DCA-MAC protocol. The selection, between the two modes of handshake, depends completely on the negotiation between the transmitter/receiver pair. During the handshake process, the transmitter and the receiver exchange their local view of spectrum usage, decide on the spectrum opportunity to use for the communication, and announce the reservation to their neighbors. On receiving a reservation control packet, neighboring nodes store the reservation information in their local spectrum allocation data structure. At the start of the reserved time period, SWITCH tunes its TRx2 to the selected spectrum band and initiates packets exchange without any delay. Details about each function of the SWITCH cognitive cycle is given in the following sections.

For spectrum mobility, SWITCH uses the concept of BC to cope with the appearance of PUs.

4.2.4 Spectrum sensing

Spectrum sensing is an essential component of the cognitive cycle of the SWITCH protocol. It is used to identify unused channels regardless of the fact that these channels are LCs or UCs. As mentioned in Section 4.2.2, each SU is equipped with two transceivers, TRx1 and TRx2. one of the main tasks of TRx2 (SDR transceiver) is to sense the unused spectrum. However, since there is only one SDR transceiver within each SU, the sensing process is very costly in terms of sensing time and energy consumption. Furthermore, an SU cannot gather accurate sensing information about the states of all the channels by itself. Thus, an efficient sensing strategy should be used to enable SUs to obtain more information about most or all channels in their vicinity.

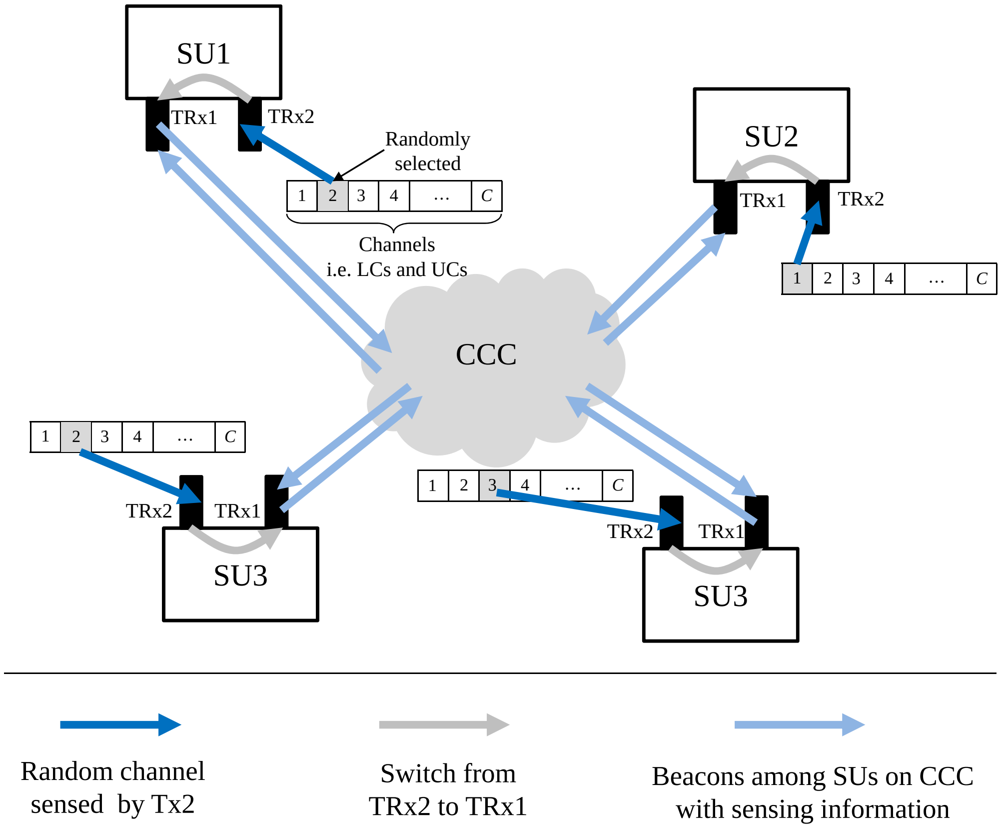


Figure 4.2: Coordination between TRx1 and TRx2 for cooperative spectrum sensing

In this thesis, we assume a simple spectrum sensing strategy. This strategy is based on cooperative spectrum sensing where the sensing results (i.e. available channels from LCs and UCs) are combined from SUs in the network. In this way, the chance of missing signals from PUs, CUs, and other SUs can be reduced which leads to better utilization of the available spectrum. To achieve this goal, coordination between both transceivers (i.e. TRx1 and TRx2), employed by each SU, is essential to sense available channels and to distribute the sensing information among SUs. Figure 4.2 illustrates the coordination procedure between both transceivers. In this figure, four SUs are located in the transmission range of each other. The SUs cooperate to gather sensing information about radio resources availability in their vicinity. The coordination between both transceivers can be described as follows:

- The SUs use the SDR transceiver, TRx2, to sense one of C channels randomly, say k-th channel, $(1 \leq k \leq C,\ C = C_1 + C_2)$ where C_1 presents the number of LCs and C_2 presents the number of UCs. We assume that each SU uses energy detection as a spectrum sensing technique to detect the channels availability [85]. The sensing process is presented by dark blue arcs and the sensed channel is represented by a gray box in Figure 4.2. We assume that each channel can be represented by an ON-OFF model. State ON means that the channel is busy and state OFF means that the channel is idle,
- If the k-th channel is idle, then the SU tunes to its TRx1 to inform other neighbors about the availability of this channel. This action is presented in Figure 4.2 by a grey arc inside each SU box,
- Then the SU uses TRx1 to send a beacon over the CCC. This action is presented in Figure 4.2 by a light blue arc,
- Clearly, if each of the C channels is sensed by at least one SU, all the SUs get information about the activity of the entire spectrum i.e. LCs and UCs.
- Since each SU randomly chooses one of C channels for sensing, it may happen that more than one SU senses the same channel. In Figure 4.2, SU1 and SU3 have sensed the same channel which is channel 2. This leads to reducing the number of sensed channels. To amend this weakness, we assume that the number of SUs is large enough to sense more channels (i.e. larger than the number of channels).

4.2.5 Spectrum allocation

Based on the collected sensing information, the spectrum allocation data structures, residing in each SU, make an adaptive decision on the operating channel defined by the center frequency and the time duration of using such a channel according to the activities of PUs, CUs and other SUs in its vicinity. The accuracy of spectrum allocation determines both the network's throughput and the overall spectrum utilization. In SWITCH, there are two spectrum allocation data structures, Neighbors Channel List (NCL), and Free Channel List (FCL).

Neighbor Channel List (NCL)

The NCL is used by each node X to keep record of the channels occupied by neighboring nodes. The NCL is constructed by listening to control messages sent on the CCC. The data structure for the NCL can be described as follows:

- $NCL(i).node$: the neighboring node i of node X. For the sake of simplicity, each node is presented by a character which is equivalent to the MAC address of the node.
- $NCL(i).ch.no$: the channel used by node i for data transmission,
- $NCL(i).ch.index$: the type of the channel (LC or UC). This field has two values, 1 or 2, which indicates if the channel is of type LC or UC, respectively. The type of the channel is assigned according to frequencies ranges. If the frequencies is ranged from 902-928 MHz, 2.4-2.5 GHz or 5.725-5.8 GHz, then the channel is assumed to be UC (i.e., $ch.index = 2$). These frequencies belong to ISM bands. Otherwise, the channels is LC (i.e., $ch.index = 2$).
- $NCL(i).time$: the duration that $NCL(i).ch.no$ is occupied (i.e. the time needed for transmission completion).

Table 4.1: Data structure for the NCL of node A

NCL(i).node	NCL(i).ch.no	NCL(i).ch.index	NCL(i).time
B	2	1	20 ms
D	4	2	15 ms
F	1	1	25 ms
.	.	.	.

Table 4.1 presents node A's NCL data structure. In this list, node A has three neighbor nodes B, D and F. These nodes utilize channels 2, 4 and 1, respectively. The $NCL(i).ch.index$ for channels 2 and 1 is equal to 1. This means that both channels are LCs. The $NCL(i).ch.index$ for channel 4 is 2. This means that this channel is UC.

Table 4.2: Data structure for the FCL of node A

FCL(i).ch.no	FCL(i).ch.index	FCL(i).ch.priority
3	1	H
5	1	M
6	2	H
7	1	L
.	.	.

Free Channel List (FCL)

This list contains the available channels in the transmission range of the node (i.e. channels not used by other neighbors). A node updates its NCL and FCL, once it receives a new control messages. The FCL can be easily generated from the NCL. The data structure for the FCL of node A, as shown in Table 4.2, can be described as follows:

- $FCL(i).ch.no$: the channel number,
- $FCL(i).ch.index$: the type of the channel (LC or UC), and
- $FCL(i).ch.priority$: This field indicates the priority of each channel to be used by the node. Each channel may be assigned one of three priorities: L, M or H which presents the channel always has low, moderate or high priority to be used, respectively. The priority is assigned to a channel according to PU and CU activities. The channel with the least PU and CU activities is given the highest priority (i.e. $FCL(i).ch.priority = H$) to be the data channel.

After maintaining the FCL, the next logical step is the selection of the Proposed data channel (PDC) and Backup channel (BC) for preparing for data transmission. The PDC is selected firstly from the LCs (i.e. channels with $ch.index = 1$) as mentioned before. The transmitter checks its FCL and selects the channel with the least PU activity (i.e. $FCL(i).ch.priority = H$) as the PDC. The BC is selected firstly from the UCs (i.e. channels with $ch.index = 2$). If all UCs are busy, the second channel with the least PU activities from the LCs, is selected as a BC.

As seen, SWITCH is flexible to choose the BC either from LCs or from UCs. The concept of BCs distinguishes the proposed protocol from state-of-the-art CR-MAC protocols and empowers the SU with the ability to quickly maintain its link in the case of PU appearance. Therefore, the time required to find a new channel in the case of PU appearance, minimizes.

4.2.6 Spectrum sharing

In this section, we describe the spectrum sharing process of SWITCH. First, we introduce the control packet format. Second, we present the two handshake modes used by SWITCH.

4.2.6.1 Control packets format

The control packet format of SWITCH is similar to the IEEE 802.11 packet format. However, some modifications are added to support the CR operation. As shown in Figure 4.3, grey fields denote extension to the 802.11 packet format. Numbers on top of each field denote the size of each field in bytes.

Request To Send (RTS)

The frame control contains the protocol version. The Duration field, in microseconds, denotes the sum of the time required to transmit the data frame, one CTS

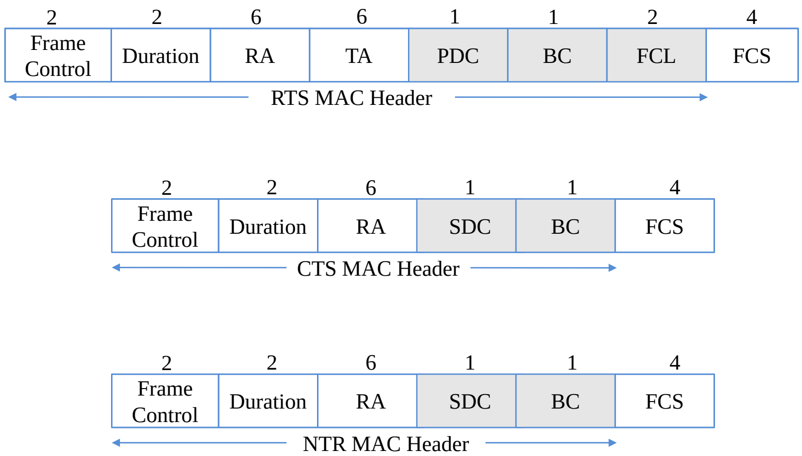


Figure 4.3: Packet format for the SWITCH protocol

frame, one *ACK* frame and three SIFS. The time in this field may vary according to the mode of the proposed protocol (see Section 4.2.6 for more details). The Receiver Address (RA) is the address of the node that will receive the data frame. The Transmitter Address (TA) is the address of the node transmitting the *RTS* frame. Three more fields are added to the packet format of the original *RTS*:

1. The *PDC* field: This field contains the proposed data channel suggested by the transmitter,

2. The *BC* field: This field contains the channel suggested in the case of the PU appearance. The *BC* is a channel selected from the UCs or LCs,

3. The *FCL* field: This field includes a list of free channels from the transmitter side,

Clear To Send (*CTS*)

The frame control contains the protocol version. The Duration field, in microseconds, is the sum of the time required to transmit the data frame, one *ACK* frame and two SIFS. The RA field is the address copied from the TA field of the previous *RTS* frame. Two fields are added to the packet format of the original *CTS*:

1. The Selected Data Channel (*SDC*) field: This field includes the data channel selected by the receiver node. This field may be equal or different to the *PDC* field in the *RTS*, this depends completely on the spectrum availability in the receiver,

2. The *BC* field which contains the channel, suggested in the case of PUs appearance.

Notification To Reserve (NTR)

This frame has the same packet format as CTS. The NTR is sent by the transmitter to its neighbors only in the case that the PDC or/and BC carried by the RTS control message is not equal to the SDC or/and BC carried by the CTS.

4.2.6.2 Handshake process

During the transmission negotiation process, the transmitter and receiver exchange their local view of spectrum usage, decide on the spectrum block to use for the communication, and announce the reservation to their neighbors. In the handshake process, the transmitter contend for spectrum access on the CCC using the random backoff mechanism of IEEE 802.11. In particular, a transmitter must first sense an idle channel for a time period equal to DIFS. Each node maintains a so-called CW, which is used to determine the number of slot times a node has to wait before transmission. The CW size is doubled when a transmission fails, i.e. when the transmitted data frame has not been acknowledged.

SWITCH has two modes of handshake. The usage of each mode depends completely on: 1) the channel availability in both the transmitter and receiver sides, and 2) the activity of PUs, CUs and other SUs. The two modes are

- Two-way RTS/CTS handshake: In this mode, the transmitter, using TRx1, sends an RTS carrying the proposed data channel (PDC), backup channel (BC) and transmitter's FCL to the receiver on the CCC. On receiving the RTS packet, if the channels indicated by PDC or/and BC are available, the receiver immediately replies with a CTS to the transmitter. A selected data channel (SDC), the same as PDC, and BC are carried in the CTS packet. Finally, both transmitter and receiver switch the TRx2 to the PDC, and the $DATA/ACK$ packets are transmitted on that channel.
- Three-way $RTS/CTS/NTR$ handshake: In this mode, an extra control packet, NTR, is sent by the transmitter to its neighbors because of the PDC or/and BC carried by the RTS control message is not equal to the SDC or/and BC carried by the CTS. Finally, both transmitter and receiver switch the TRx2 to the selected data channel, and the $DATA/ACK$ packets are transmitted on that channel. The purpose of the NTR packet is to notify the transmitter's neighbors for updating their $NCLs$.

For the sake of simplicity, we give an example. Suppose that we have five SUs: A, B, C, D and E. We assume that all users are within radio range of each other, as shown in Figure 4.4. Each user constructs its FCL during the spectrum sensing process. There are two types of channels: four LCs and two UCs. One of the LCs ($Ch.no = 1$) is selected as a CCC. In addition, two LCs are available for transmission: $Ch.no = 2$ and $Ch.no = 3$, respectively. Furthermore, $Ch.no = 5$ from UCs is available. Both $Ch.no = 4$ from LCs and $Ch.no = 6$ from UCs

FCT for node B

Ch.no	Ch.index	Ch.priority
1	1	-
3	1	H
2	1	M
5	2	H

FCT for node C

Ch.no	Ch.index	Ch.priority
1	1	-
3	1	H
2	1	M
5	2	H

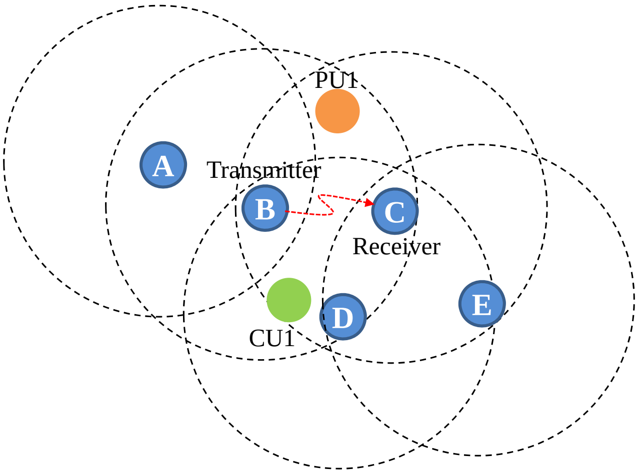


Figure 4.4: Node B communicates with node C depending on FCL

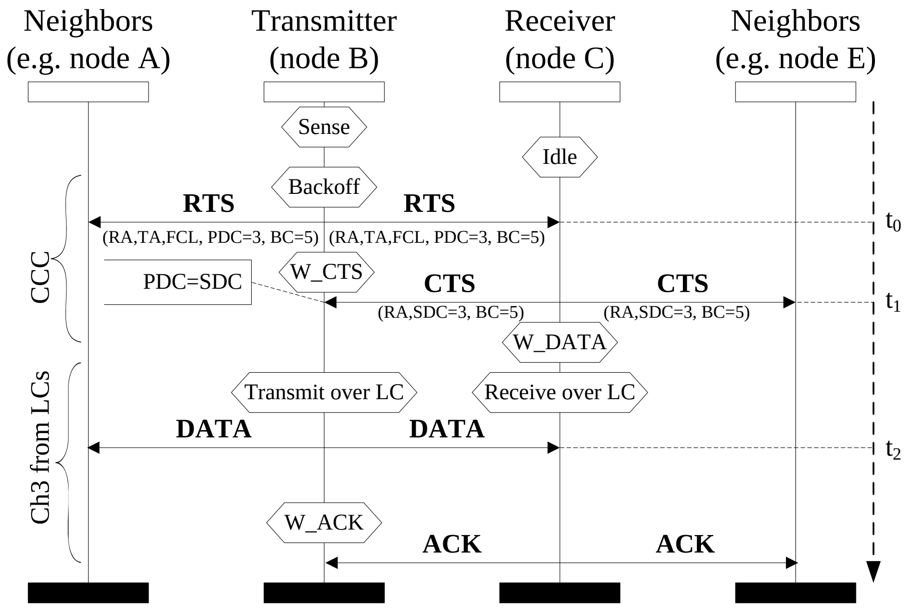
are utilized by PU1 and CU1, respectively (i.e., both channels are busy). This explains why those channels are not listed in the FCL.

To establish a communication between B and C, the nodes use one of the previously mentioned handshake modes. To simplify the description of these scenarios, Message Sequence Charts (MSC) [86] are used. Generally, the MSC is used for describing a specific execution sequence of the system. Thus, a MSC mainly represents a kind of sequence diagram. In the terminology of MSC, it specifies how messages are passed through the instances of the system. The instances, in our example, are the transmitter, the receiver and the neighbors. Messages like $RTS, CTS, NTR, DATA$ and ACK are presented by arrows. The state of an instance is graphically specified using a hexagon.

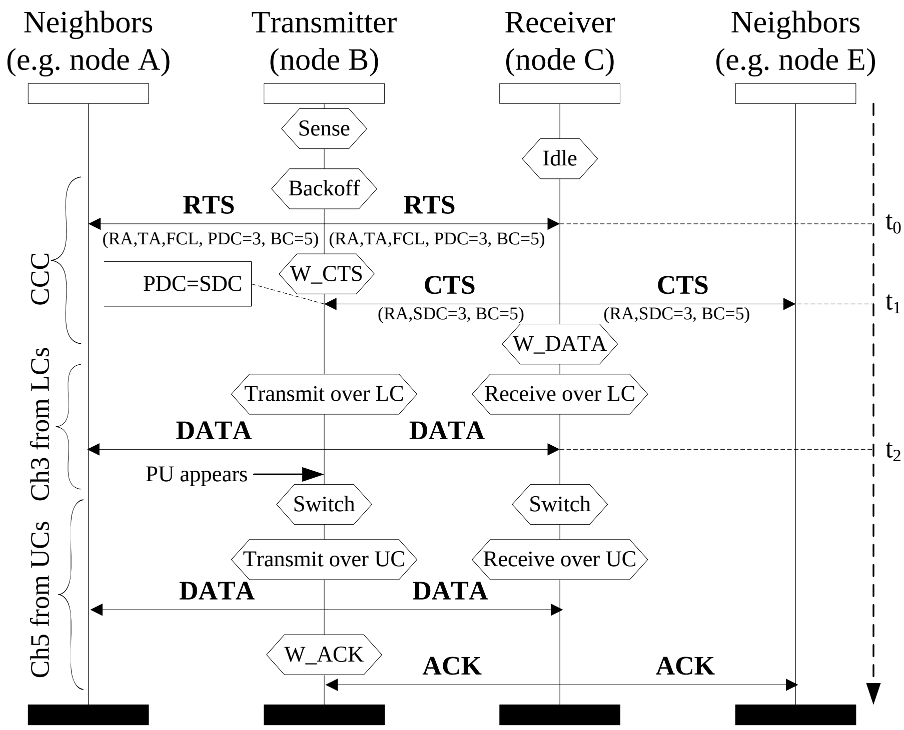
Two-way RTS/CTS handshake

In this scenario, the normal handshake RTS/CTS based on IEEE 802.11 MAC is used. Figure 4.5-a presents the MSC for this scenario. Four instances are involved in this figure: The transmitter's neighbors (e.g. node A), the transmitter (node B), the receiver (node C) and the receiver's neighbors (e.g. node E). In this scenario, the transmitter (node B) follows the IEEE 802.11 MAC protocol to access the CCC and starts the negotiation process. The transmitter must first sense an idle channel for a time period equal to DIFS and selects a random backoff if the channel is busy. This explains the existence of Sense and Backoff states in the figure. After a successful contention, the following message sequence exchange happens:

1. At time t_0, the transmitter (i.e. node B) sends an RTS to the receiver (node C). The RTS packet contains the following fields: RA, TA, FCL, PDC and



(a) Without SU interruption



(b) With SU interruption

Figure 4.5: MSC for RTS/CTS handshake

BC which represent the receiver address, transmitter address, transmitter free channel list, proposed data channel and the backup channel, respectively. In this scenario, the transmitter selects $Ch.no = 3$ as a PDC and $Ch.no = 5$ as a BC. After sending RTS, the transmitter transits to the *W-CTS* state (i.e. Waiting for CTS).

2. On receiving RTS, the following procedure is prompted on the receiver and the neighboring nodes:

   - The receiver (i.e. node C) checks if PDC and BC are available on its FCL or not. If both channels are available, node C replies a CTS to node B at t_1 and agrees with node B's proposal by setting both SDC and BC to channels 3 and 5, respectively. In addition, node C tunes its TRx2 to the selected data channel (i.e. $Ch.no = 3$) from LCs and transits to *W-DATA* state (i.e., waits for data transmission).
   - Neighboring nodes, such as node A, update their NCL accordingly. Furthermore, node A will reserve the channel within PDC field tentatively for a time equal to $Duration_{RTS}$. The duration field of the RTS can be listed as follows: $Duration_{RTS} = T_{CTS} + T_{ACK} + 3SIFS + T_{DATA}$. This reservation prevents node A from transmitting in such a channel. If node B does not send any additional control messages, the reservation will be confirmed.

3. On receiving CTS, the following procedure is prompted on the transmitter (node B) and the neighboring nodes:

   - Node B checks if the PDC is equal to the SDC. If so, it tunes its TRx2 to the selected data channel (i.e. $Ch.no = 3$) from LCs. Moreover, both transmitter and receiver transit to states *Transmit over LC* and *Receive over LC*, respectively.
   - Neighboring nodes, such as node E, update their NCL accordingly. Furthermore, node E will reserve the channel given by the SDC field, this reservation prevents node E from transmitting in such channel. The channel will be reserved for a time equal to $Duration_{CTS}$. The duration field of the CTS can be listed as follows: $Duration_{CTS} = T_{ACK} + 2SIFS + T_{DATA}$, where T_{ACK} and T_{DATA} presents the time needed to transmit ACK and DATA, respectively.

4. At t_2, as a result of the successful handshake, data transmission is established between B and C. Afterwards, ACK is sent by the receiver to acknowledge the reception of the data packet.

If a PU appears during the data transmission between B and C, both nodes wait for a time, T_{Switch} and then switch to the BC ($Ch.no = 5$) from the UCs if available. T_{Switch} can be defined as the time required by the SU to sense and switch to the BC. This process is called spectrum mobility. The spectrum mobility process can be defined as the process when an SU changes its frequency of operation due to the appearance of PUs. This process is presented by the *Switch state* in Figure 4.5-b. There is no need to inform the neighboring nodes about such a switch since they are already informed before by listening to the RTS and CTS. The T_{Switch} time should be less than DIFS. If this condition is not satisfied then there is a probability that another SU in the vicinity of the transmitter wins the contention and thus the switching fails. If the BC is available, both users will not perform any additional handoff since the UCs are free from PUs and thus both transmitter and receiver transit to states *Transmit over UC* and *Receive over UC*, respectively. If the BC is not available, the transmitter/receiver pair restart the negotiation process again as presented in the aforementioned scenario.

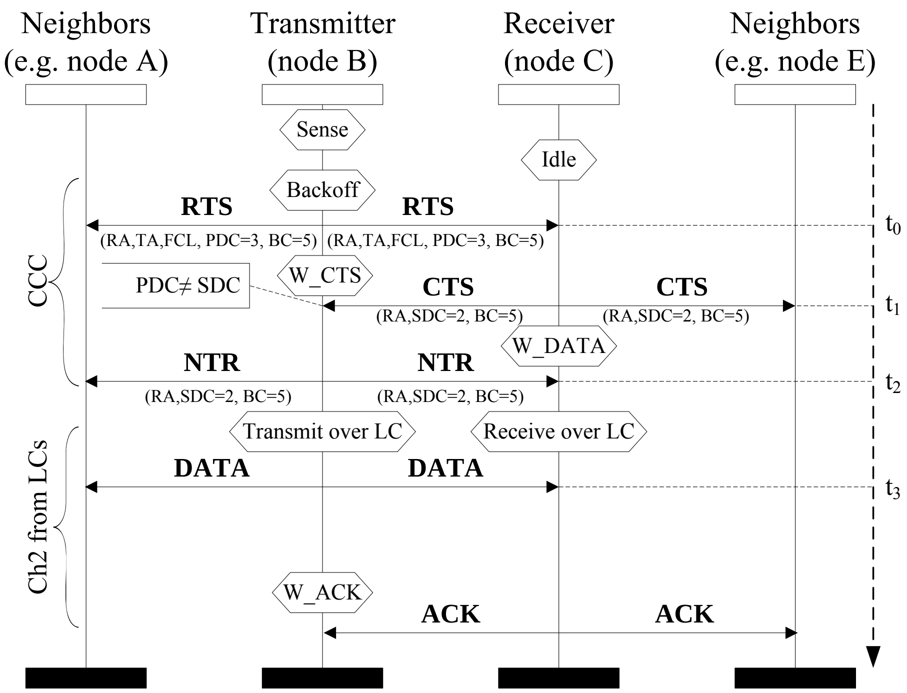
Three-way $RTS/CTS/NTR$ handshake:

In this scenario, a new extra control packet, named NTR, is added to the normal RTS/CTS handshake. The reason behind adding the NTR packet is the difference between the PDC or/and BC carried by the RTS packet and the SDC or/and BC carried by the CTS packet. To explain the MSC for such a case, we use the same network topology presented in Figure 4.4 with different channels availability in nodes C. We assume that $Ch.no = 3$ from LCs is not included in the FCL of node C (i.e., $Ch.no = 3$ is busy). The MSC for this scenario, as shown in Figure 4.6-a, can be explained as follows:

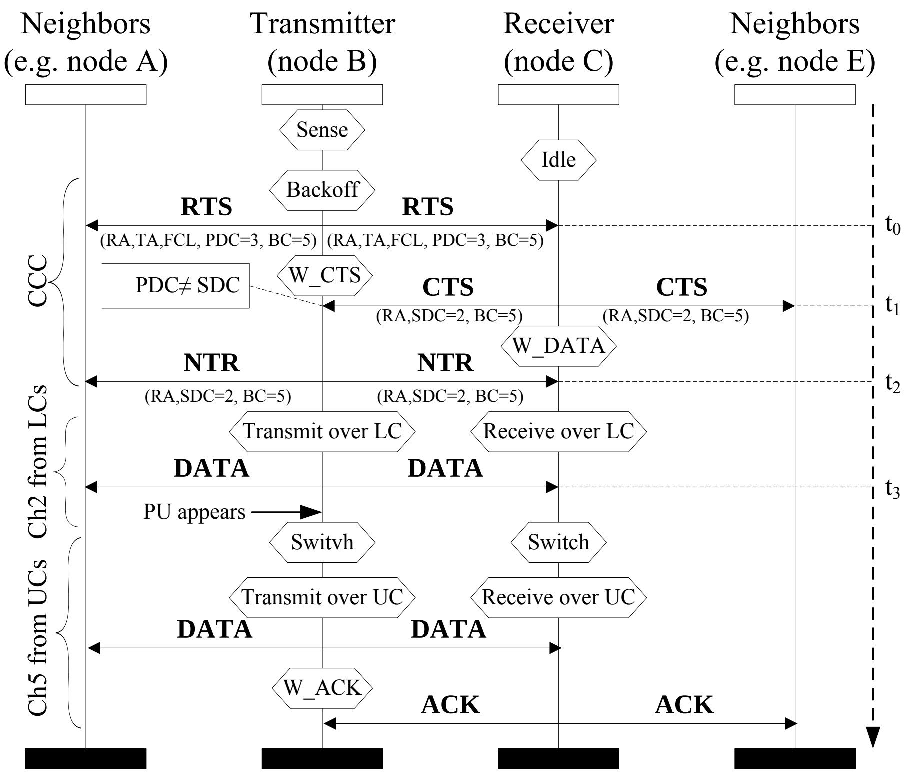
1. At time t_0, the transmitter (node B) sends an RTS to the receiver (node C). In this scenario, the transmitter selects $Ch.no = 3$ as a PDC and $Ch.no = 5$ as a BC. Furthermore, the transmitter switches to the *W-CTS state*.

2. On receiving of the RTS, the following procedure is prompted on the receiver and the neighboring nodes:

   - The receiver (node C) checks the availability of $Ch.no = 3$ in its FCL. Node C finds that $Ch.no = 3$ is not listed there (i.e. busy). Therefore, node C selects another data channel. The selection of a new data channel is done as follows: Node C matches both its FCL with the FCL of node B. Based on this matching, C selects $Ch.no = 2$ from LCs as the SDC and sends a CTS, at time t_1, carries the new information. Furthermore, node C transits to the *W-DATA state* . In this state, node C waits for a time equal to $SIFS + T_{NTR}$ and then tunes its TRx2 to the selected data channel (i.e. $Ch.no = 2$) from LCs.



(a) Without SU interruption



(b) With SU interruption

Figure 4.6: MSC for $RTS/CTS/NTR$ handshake

- Neighboring nodes such as node A update their NCL accordingly. Furthermore, node A will reserve the channel within PDC field tentatively for a time equal to $Duration_{RTS}$. The duration field of the RTS can be listed as follows: $Duration_{RTS} = T_{CTS} + T_{ACK} + 3SIFS + T_{DATA}$. This reservation prevents node A from transmitting in such channel. If node B does not send any additional control messages, the reservation will be confirmed.

3. At time t_1, on receiving the CTS, the following procedure is prompted on the transmitter (node B) and the neighboring nodes:

   - Node B checks if the PDC is equal to SDC. Node B finds that the data channel in both fields PDC and SDC is different (i.e. NTR should be sent to inform the neighbors about such difference)
   - Neighboring nodes such as node E update their NCL accordingly. Furthermore, node E will reserve the channel given by the SDC field, this reservation prevents E from transmitting in such channel. The channel will be reserved for a time equal to $Duration_{CTS}$. In such a case, the $Duration_{CTS}$ is different from the one presented in the first scenario. The duration field of the CTS in this scenario can be listed as follows: $Duration_{CTS} = T_{ACK} + T_{NTR} + 3SIFS + T_{DATA}$.

4. At time t_2, node B sends a NTR message to its neighbors to update their NCL. The neighboring nodes change the tentative reservation that happened for the PDC as a response to the RTS with the new information carried by the NTR message. The channel indicated by SDC will be reserved in the NCL for a time equal to: $Duration_{NTR} = T_{ACK} + 2SIFS + T_{DATA}$. Furthermore, node B tunes its TRx2 to the selected data channel ($Ch.no = 3$) from LCs.

5. At time t_3, as a result of the successful $RTS/CTS/NTR$ handshake, data transmission is established between B and C.

Another scenario can happen as shown in Figure 4.6-b. In this scenario, the PU appears during the data transmission between B and C. In such a case, both nodes will wait for T_{Switch} and after that switch to the BC from the UCs if available. There is no need to inform the neighbor nodes with this switch since other nodes are already informed before by overhearing the RTS, CTS and NTR. If the BC is available, both users will not perform any additional handoff since the UCs are free from PUs.

It is possible that after performing a channel switching, the transmitter or the receiver find the BC to be busy, this may occur due to one of the following reasons:

- Conflicting reservations due to loss of control packets.

- An CU occupies the BC since we assume a soft reservation of the BC. Soft reservation means that the BC can be utilized by other CUs if there is no free UC.

4.2.7 Protocol state machine

The SWITCH protocol behavior can be described in further details by the state machine diagram shown in Figures 4.7.

The state machine can be divided in two parts: 1) Transmitting procedure and 2) Receiving procedure. The descriptions of the states and their transition when the SU transmits data, is given as follows:

Idle state: Initially, the SU is in the *Idle state* until it has data to send. The transition from the Idle state is triggered by the arrival of a packet from the upper layer. Thus, the SU transits to the *Sense state*.

Sense state: Before the SU starts a transmission, it has to keep sensing the CCC for an additional random time after detecting the channel as being idle for a minimum duration called DIFS. The SU is allowed to initiate its transmission only when the CCC is sensed idle for this time duration. The SU uses two sensing mechanism, the PCS and the VCS, like IEEE 802.11 MAC described in Chapter 2.

Backoff state: The SU uses a backoff mechanism which represents the amount of time that must elapse while there are not any transmissions, i.e., the medium is idle before the listening station may attempt to begin its transmission again. The backoff procedure was described in detail in Chapter 2. The transition from the backoff state is triggered when the backoff timer =0. In such a case, the SU is ready to send the RTS packet and therefore the SU switches to *S-RTS state*.

S-RTS state: In this state, the SU starts sending the RTS packets to its intended receiver. Three additional fields which are PDC, BC and FCL are carried by the RTS as mentioned before. The transition of *S-RTS* state is triggered by a successful transmission of the RTS and the SU transits to the *W-CTS state*.

W-CTS state: In this state, the SU waits for a CTS reply from its intended receiver. Two triggers are possible for this state: (1) there is no CTS and the SU reaches the maximum retry limit as IEEE 802.11. In such a case, the SU transits to the *Backoff state* again. (2) the arrival of a CTS reply. In such a case, the SU has to check the SDC field in the CTS packet. If the data channel is equal in both the PDC field and the SDC field, the SU tunes its TRx2 and starts the data transmission after SIFS over this channel. Thus, it switches to the *Transmit over LC state*. If not, the data transmission will start over the new channel indicated in SDC field. In such a case, it transits to the *S-NTR state* to inform neighboring nodes that there is a change in the data channel.

S-NTR state: As mentioned from the *W-CTS state*, the SU sends the NTR packet if the channel indicated by PDC is different from the one indicated by

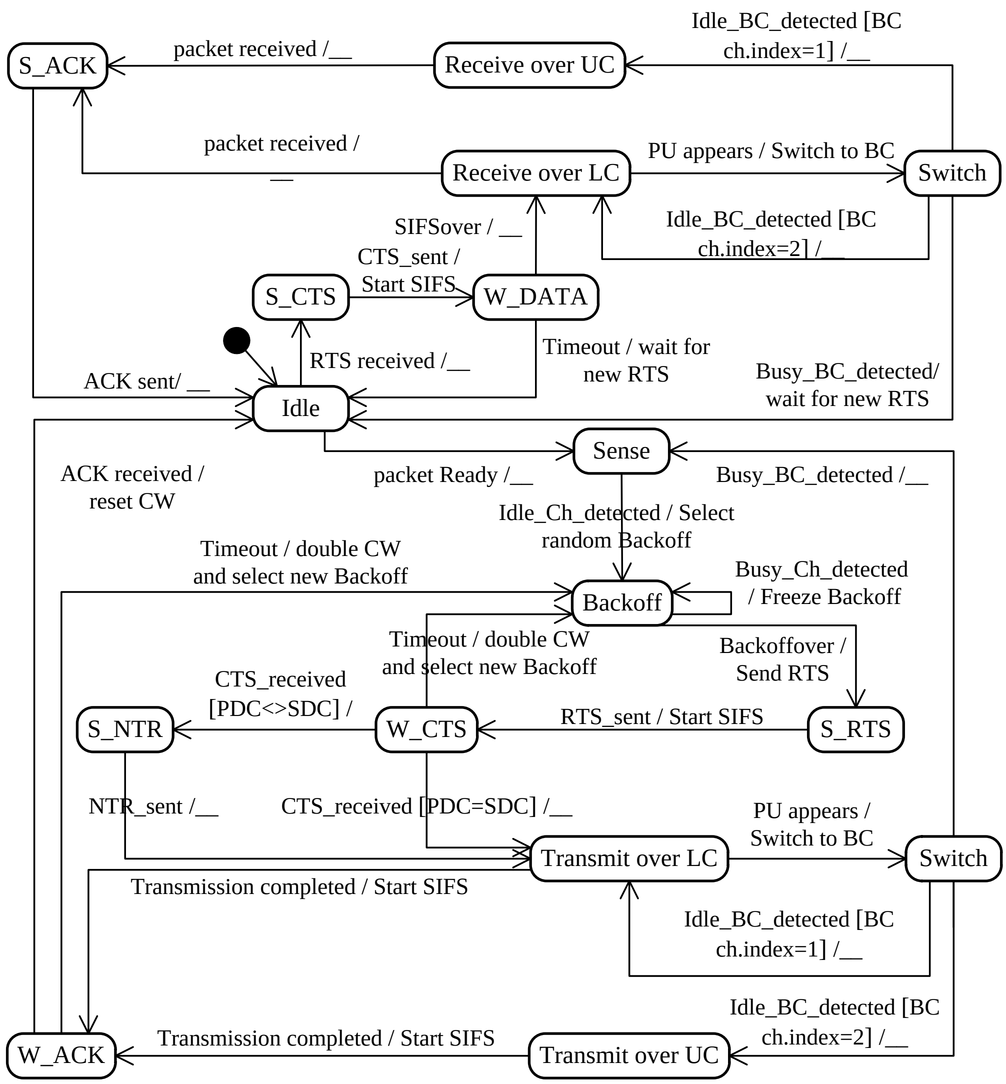


Figure 4.7: State machine diagram for SWITCH

SDC. Thus, it sends the NTR packet to notify its neighbors for updating their NCL. The transition from this state is triggered by a successful transmission of the NTR packet and thus the SU transits to the *Transmit over LCs state*.

Transmit over LCs state: In this state, the SU tunes its data transceiver (TRx2) to the data channel and starts its transmission over the LCs. The transition from this state is triggered by one of the two following events. The first one is: a successful data transmission and thus the SU switches to the *W-ACK state*. The second one: the appearance of a PU and therefore the SU transits to the *Switch state*.

Switch state: In this state, the SU switches its Trx2 to the intended BC and senses this channel for a time T_{Switch}, where $SIFS < T_{Switch} < DIFS$. The transition from this state is triggered by one of the three following events. The first one is: the BC is sensed free and the BC $ch.index = 1$, thus the SU starts a transmission over a channel from the LCs and transits to the *Transmit over LCs state* again. The second one is: the BC is sensed free and the BC $ch.index = 2$, thus the SU starts a transmission over a channel from the UCs and switches to the *Transmit over UCs state*. The third one is: the SU failed to switch to the BC and thus transits to the *Sense state* again.

Transmit over UCs state: In this state, the SU starts its transmission over the UCs. The UCs have the advantage that once the SU starts its transmission, no interruption will happen since the UCs are free from the PUs. The transition from this state is triggered by the completion of the data transmission and thus the SU transits to the *W-ACK state*.

W-ACK state: In this state, the SU waits for a ACK reply from its intended receiver. The transition from this state is triggered by two events. The first one is: there is no ACK received. In such a case, the SU transits to the *Backoff state* and starts to send the data packet again. The second one is: the arrival of ACK reply. In such a case, the SU transits to the *Idle state* and the data transmission is ended.

In addition, the following states happen when the SU receives data. The descriptions of these states and their transition can be given as follows:

S-CTS state: Upon receiving the RTS packet, the SU checks if the channel indicated by PDC is available in its FCL. If so, the SU waits for SIFS and replies with a CTS to the transmitter. In such a case, the channel in the SDC, the same as the one in PDC, is carried in the CTS. If the PDC is not available, the SU checks its FCL and the FCL of the transmitter, and selects a SDC that is available for both nodes. Once the SDC is selected, the SU sends a CTS with the new channel to the transmitter. The transition from this state is triggered by the transmission of the CTS packet and thus the receiver transits to the *W-DATA state*.

W-DATA state: After sending the CTS, the SU waits for data for a time equal to SIFS if PDC equals to SDC. Otherwise, the SU waits for $2SIFS + T_{NTR}$. If the time is expired and no data is received, the receiver goes to *Idle* *state* again. If not, the SU starts receiving the data over the LCs. The transition from this state is triggered by the arrival of the first data frame and thus the receiver transits to the *Receive over LCs state*.

Receive over LCs state: In this state, the SU tunes its data transceiver (TRx2) to the data channel and starts receiving data. The transition from this state is triggered by one of the two following events. The first one is: the data is received successfully and thus the SU enters the *S_ACK state*. The second one: A PU appears and therefore the SU transits to the *Switch state*.

Switch state: In this state, the SU switches its TRx2 to the intended *BC* and waits for the data from its intended transmitter. The transition from this state is triggered by one of the three following events. The first one is: the *BC* is sensed free and the *BC ch.index* = 1, thus the SU starts receiving the data again over a channel from the LCs and enters the *Receive over LCs* state again. The second one is: the *BC* is sensed free and the *BC ch.index* = 2, thus the SU starts receiving the data over a channel from the UCs and transits to the *Receive over UCs state*. The third one is: the SU fails to switch to the *BC* and thus goes to the *Idle state*.

Receive over UCs state: In this state, the SU starts receiving the data over the UCs. The UCs have the advantage that once the SU starts its transmission, no interruption will happen since the UCs are free from the PUs. This state is triggered by receiving the data successfully and thus the SU transits to the *S-ACK state*.

S-ACK state: After a successful reception of the data, the SU sends an *ACK* to its intended transmitter. Once the SU sends the *ACK*, it transits to the *Idle state* again.

From the aforementioned description of SWITCH, the time needed by each SU to have a successful transmission, T_{succ}, is given as follows:

$$T_{succ} = \begin{cases} T_{RTS} + T_{CTS} + T_{ACK} + 3SIFS + L & for PDC = SDC \\ T_{RTS} + T_{CTS} + T_{ACK} + 3SIFS + T_{Switch} + L & for PDC = SDC, \text{ PU appears} \\ T_{RTS} + T_{CTS} + T_{NTR} + T_{ACK} + 4SIFS + L, & for PDC \neq SDC \\ T_{RTS} + T_{CTS} + T_{NTR} + T_{ACK} + 4SIFS + T_{Switch} + L, & for PDC \neq SDC, \text{ PU appears} \end{cases}$$

and the time spent if a collision happens, T_c, can be give as follow

$$T_c = T_{RTS} + DIFS$$

where $L = DIFS + T_{DATA}$

4.3 Simulation

The effectiveness of the SWITCH protocol is extensively evaluated by a discrete event simulator. SWITCH is comparatively evaluated along with a modified version of the IEEE 802.11 multichannel MAC protocol, named CR-MAC protocol and the DCA-MAC protocol. As saturation throughput is a major performance measure to evaluate MAC protocols [23, 87, 88], we use it as the main performance metric through the simulation. The saturation throughput means that SUs always have data packets in their queue to transmit. In this section, a description about the developed simulator is introduced. The description includes simulator assumption, parameters and scenario.

Simulator description

We have developed a discrete-time simulator to evaluate the performance of the SWITCH protocol. JAVA was our design choice since we needed a rapid prototyping functionality and overall control over the simulator development process. The developed simulator is a coarse-grained simulator. A coarse-grained simulator means that it omits some of the transient effects related to connection establishment such as the backoff mechanism. This simplification gives enough information to focus on the interactions between the SUs, resulting in a fast development time. We believe that the differences between CR-MAC protocols arise mainly from their rendezvous mechanisms, the interaction after a PU appearance and not from the way CSMA backoff parameters affect them.

In [23], the authors have explained in detail that each user can access the channel randomly among all the nodes contenting for a channel with a probability of success, p_{succ} (agreement is made) or with a probability of failure, $(1 - p_{succ})$ (no agreement is made). The authors have shown that the optimal value for p_{succ} is $e^{-1} = 0.37$. The justification of introducing such value is presented with more details in [23]. By selecting the previous value of p_{succ}, the authors came up with the conclusion that this value can mimic the long-term behavior of CSMA/CA. In our simulator, it is important to mention that the aforementioned approximation will be used for all CR-MAC protocols and therefore it will result in a fair comparison.

Simulation assumptions

The assumption made by the simulation can be listed as follows:

1. There are two types of channels: LCs and UCs. State-of-the-art CR-MAC protocols utilize only the LCs and the SWITCH protocol utilizes both, LCs and UCs.

2. Each LC is assumed to be occupied with PU packet based traffic, and the average PU occupancy level is the same for all channels. Each UC is

assumed to be occupied with SU or CU packet based traffic.

3. The maximum number of LCs and UCs are assumed to be C_1 and C_2, respectively.

4. The packets arrival process for PUs, SUs and CUs are assumed to be Poisson with rates λ_1, λ_2 and λ_3, respectively.

5. There is one channel used as CCC and this channel is assumed to be free from PUs.

6. The packet service time for PUs, SUs and CUs are assumed to be fixed and equal to 18.4 ms, which represents the time needed to send a packet of size 2300 Byte.

7. The SUs are assumed to be completely transparent for the PUs. Therefore, there is no impact of SUs on PUs performance.

8. Immediate preemption of an SU upon the appearance of a PU. In state-of-the-art CR-MAC protocols, the preempted SU makes a new negotiation with its intended receiver. In the SWITCH protocol, the preempted SU switches its Trx2 to the intended BC and senses this channel for a time T_{Switch}, where $SIFS < T_{Switch} < DIFS$. If the BC is idle, the transmission continues over this channel. Otherwise, a new negotiation between the transmitter and the receiver should be established (see Section 4.2.7).

9. The SUs under consideration are all homogeneous, i.e. statistically identical and independent.

10. The time in the developed simulator is divided into small slots. Each time slot is enough to exchange RTS/CTS packets.

11. The channels are noise-free, so that packets are lost only because of collisions.

12. We increase the load by correspondingly increasing the packet arrival rate of the Poisson process (the packet size is kept fixed).

13. We assume that each SU has always a packet to transmit.

14. The transmission ranges of PUs, SUs and CUs are 150m, 50m and 50m, respectively.

15. Each SU tracks the status of each channel by listening to control packets on the CCC. Based on the received information, each SU establishes two tables. The first one is NCL, which includes the channels occupied by the neighbors and the second one is FCL, which contains the free channel in each SU and can be calculated easily from the NCL.

16. Each SU uses a single First-In First-Out queue of infinite size. Therefore, the simulation results are not affected by the issues of finite buffer size such as dropping. However, if a packet transmission attempt reaches a Max retransmission attempt (i.e., number of attempts =7 like IEEE 802.11), then the packet is dropped.

17. We assume that all nodes in the networks are static.

18. All reported results are averages over three different run of the simulation. Each run is equal to transmit 30,000 SU packets on aggregate.

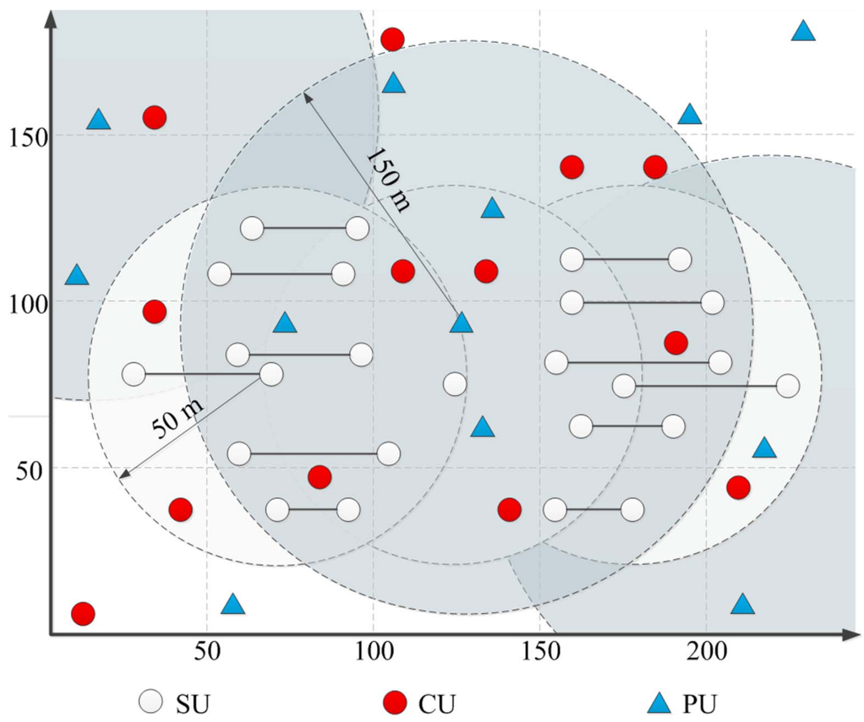


Figure 4.8: The simulation scenario: 24 SUs coexist with PUs and CUs

Simulation scenario and parameters

We mainly focus on the scenario where all SUs utilize LCs and UCs used by the same set of PUs and CUs, respectively. This implies that the LCs and UCs availability information sensed by each SU is consistent among all SUs. The scenario used in our simulation can be described as follows: There are 24 SUs, 12 CUs and 12 PUs. SUs are static. Each two SUs establish a session. We assume that each SU has always a packet in its queue to send. The SUs coexist with both the PUs and the CUs. Each SU in this network independently generates a traffic of a fixed-size packets. Figure 4.8 shows the simulation scenario. Furthermore, simulation parameters are presented in Table 4.3.

Table 4.3: Simulation parameters

Parmeter	Value
Data rate	1 Mbps
Number of LCs and UCs	varies
Transmission range for PUs	150m
Transmission range for SUs	50m
Transmission range for CUs	50m
Slot time	20μs
RTS size	24 Byte
CTS size	16 Byte
NTR size	16 Byte
DATA size	2300 Byte
ACK size	14 Byte
SIFS	10μs
DIFS	50μs
T_{Switch}	40μs

Comparison with other MAC protocols

SWITCH is comparatively evaluated along with CR-MAC and DCA-MAC. The description for both protocols can be listed as follows:

CR-MAC protocol: The CR-MAC protocol is a modified version of the IEEE 802.11 MAC protocol. The modification mimics and supports multichannel access methods. Like SWITCH, CR-MAC also uses a dedicated CCC for control packets exchange while using other channels for data communications. The data channels are assigned from the LCs only and other UCs are ignored. Thus, CR-MAC is operating only over the LCs. CR-MAC works as follows: When the transmitter has a data packet to send to its intended receiver, the following sequence of steps is executed:

1. The transmitter senses the CCC using its TRx1 and if it is idle, it sends a RTS. The RTS message contains a list of the available channels at the transmitter side,

2. Upon receiving the RTS, the receiver checks if one of the channels listed in the RTS exists on its free channels list. If so, the receiver sends CTS with the selected data channel and tunes its TRx2 to this data channel. If there is no match between the lists, the receiver stays on the CCC for a new request,

3. Upon receiving the CTS, the transmitter tunes its TRx2 to the selected data channel and starts data transmission,

4. Once the packet transmission is completed, the receiver replies with ACK message to confirm that data is transmitted successfully,

5. If a PU appears during the data transmission, the steps from 1-4 are repeated.

DCA-MAC protocol: The second protocol is the DCA-MAC protocol [39]. In DCA-MAC, each node is equipped with two transceivers TRx1 and TRx2. The TRx2 is always tuned to the appropriate data channel while the TRx1 is used for performing spectrum scanning and sending or receiving control packets on the CCC. Furthermore, in DCA-MAC, each node stores two data structures: the Current Usage List (CUL) and the Free Channel List (FCL). Furthermore, spectrum pooling is used to gather information about the utilization of every channel and hence to store this information in the CUL. The main procedure used by DCA-MAC to establish a connection between transmitter/receiver pair can be listed as follows:

1. The transmitter uses its TRx1 to sense the CCC and if it is idle, the transmitter sends a RTS to the receiver carrying its FCL,

2. Upon receiving the RTS, the receiver matches the transmitter's FCL with its FCL to identify a data channel (if any) to be used in their subsequent communication and replies with CTS to the transmitter. The receiver also tunes its TRx2 to the selected data channel while waiting for receiving the data,

3. Upon receiving the CTS, the transmitter sends a RES (reservation) message to inhibit its neighboring nodes from using the same channel,

4. The transmitter tunes its TRx2 to the selected data channel,

5. Once the packet transmission is completed, the receiver replies with an ACK message to confirm that the data is transmitted successfully,

6. If a PU appears during the data transmission, the steps from 1-5 will be repeated.

The main differences between the SWITCH protocol and the other two MAC protocols can be listed as follows:

- Different from the other two protocols, SWITCH operates over both LCs and UCs,

- The PDC field, which contains the proposed data channel, is piggybacked with the RTS packet. This feature gives SWITCH an advantage over the other two protocol. If the data channel is available on the receiver side, there is no need to send a RES message as in the DCA-MAC protocol. This minimizes the control overhead compared to DCA-MAC,

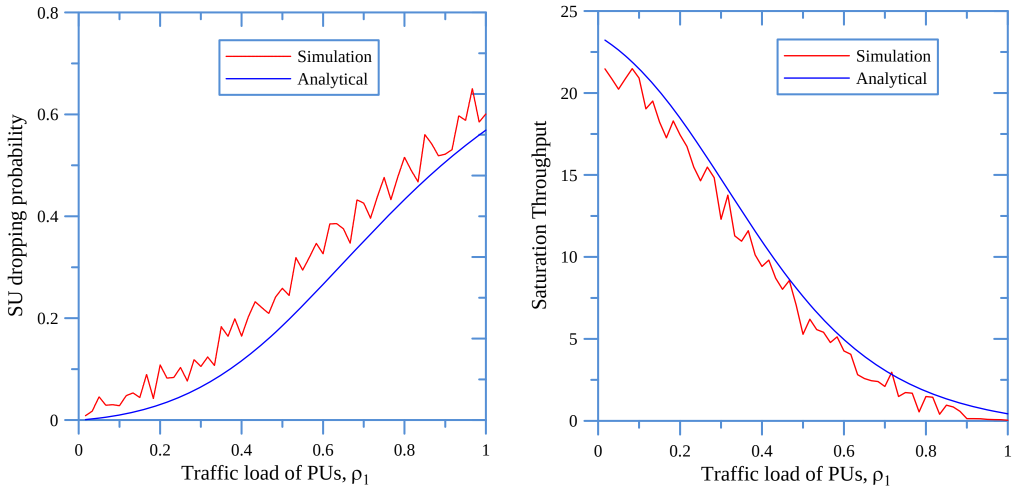


Figure 4.9: Dropping probability and saturation throughput for SUs as a function of PU traffic load for both the analytical model and simulation:$C_1 = 10$ and $C_2 = 2$

- The *BC* field, piggybacked with the *RTS* packet in SWITCH, gives the opportunity for both transmitter and receiver to react efficiently to the appearance of the PUs. On the contrary, when the PU appears, a new agreement is needed to maintain the SU's link in CR-MAC and DCA-MAC protocols.

4.4 Results

After presenting the simulation description, we now introduce the simulation results. The main focus of the results is the saturation throughput as mentioned before. Simulation results are given as a function of the PU traffic load since the appearance of PUs is the most important event that affects CR ad hoc networks.

Validation of the analytical model

To validate the results, obtained from the analytical model in Chapter 3, the following parameters are used: $C_1 = 10$, $C_2 = 2$, $0.01 < \lambda_1 < 0.5$, $\lambda_2 = 0.9$, $\mu_1 = 0.05$ and $\mu_2 = 0.05$. Furthermore, we assume that the two UCs are free from CUs.

Figure 4.9 depicts the SU dropping probability and throughput for both the analytical model and simulation as a function of PU traffic load ρ_1 ($\rho_1 = \lambda_1 / C_1 \mu_1$). The difference between the analytical and simulation results is acceptable. We can explain that as follows: the analytical model assumptions, presented in section 3.5.1, are consistent with simulation assumptions, numbered from 1-9. However, the simulation presents more assumptions numbered from

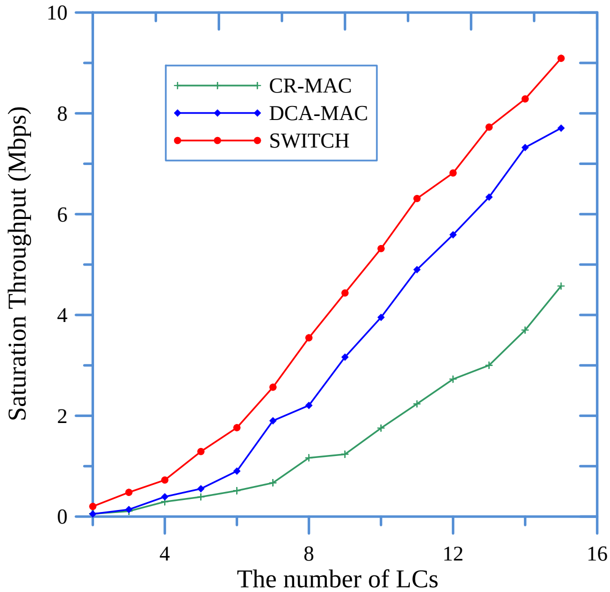


Figure 4.10: Saturation throughput of the SUs as a function of the number of LCs:$\rho_1 = 0.5$

10-18. These assumptions give more details about channel negotiation, timing, etc. Thus, the analytical model results outperform simulation results since the analytical model assumes a neglectable time for sensing and negotiation.

After ensuring the accuracy of the analytical model, we evaluate the SWITCH protocol in terms of saturation throughput and we compare it with CR-MAC and DCA-MAC protocols. The saturation throughput is extensively evaluated with different parameters such as the number of LCs, the number of UCs, different traffic load of CUs and different data rates.

Impact of the number of LCs

Here, we show the impact of the number of LCs on the saturation throughput. We assume that all LCs are occupied by the PUs uniformly and equally except for the CCC which is assumed to be free from PUs. The traffic load for the PUs, ρ_1 is 0.5. The number of SUs is always twice the number of channels. We use the simulation parameters presented in Table 4.3. Obviously, increasing the number of LCs leads to an increase of the throughput for each of the three MAC protocols as shown in Figure 4.10. However, SWITCH performs better compared to CR-MAC and DCA-MAC. The BC concept used in SWITCH, gives the SU a higher chance to re-establish its transmission quickly in case of the appearance of a PU without sending any additional control messages. In the contrary, a new agreement between transmitter/receiver pair has to be established in both CR-MAC and DCA-MAC as a response to PU's appearance. This leads to an

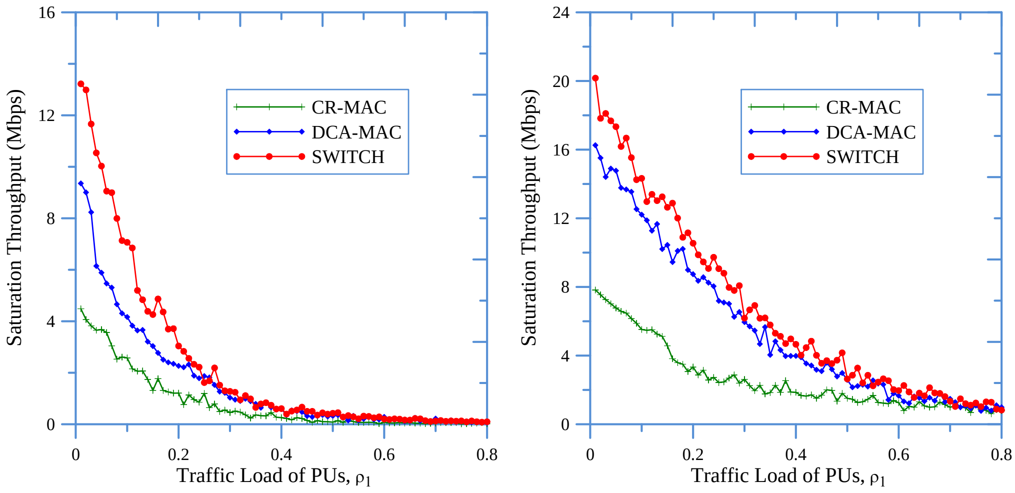


Figure 4.11: Saturation throughput of the SUs as a function of PU traffic load ρ_1 and using the LCs only: (a)$C_1 = 6$ and $C_2 = 0$ and (b)$C_1 = 12$ and $C_2 = 0$

increase of the data collisions in the CCC and therefore decreases the throughput of the two protocols.

Impact of PU traffic load

The PU traffic load, ρ_1 has a great impact on the performance of SUs since once a PU appears in a channel occupied by an SU, the SU should vacate this channel and determine another free one. This process continues till the SU has retransmitted the interrupted packet completely. Therefore, a network with a low PU traffic load will give the opportunity to SUs to operate over the LCs with minimum interruption.

Figure 4.11-a shows the saturation throughput of the SUs using the SWITCH protocol compared to DCA-MAC and CR-MAC vs. the PU traffic load and using the LCs only. The number of LCs is set to 6 or 12 channels. In addition, the number of SUs is 24. In this Figure, the impact of the UCs is not shown. Obviously, when the PUs traffic loads increase, the throughput for the three MAC protocols decreases however with different levels. Since not all three MAC protocols access the channel the same way, they grab the available channels with varying efficiency. This explains the different slopes for the different MAC protocols. Although the UCs are not used here, the performance of SWITCH outperforms the performance of the other two protocols. The throughput of SWITCH increases compared to CR-MAC and DCA-MAC by 91% and 19%, respectively.

This can be explained as follows: Firstly, unlike CR-MAC and DCA-MAC, the proposed data channel is carried by the RTS control message in SWITCH. Thus, the neighboring nodes are informed in advance about this channel which

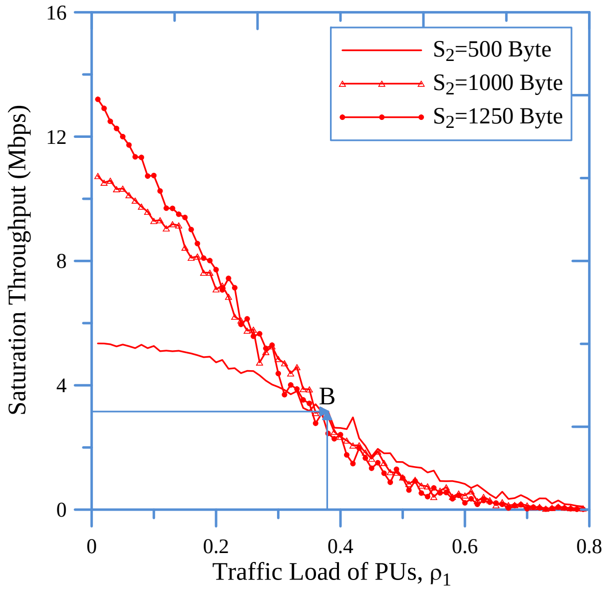


Figure 4.12: Saturation throughput of the SUs in SWITCH as a function of PU traffic load ρ_1 with different SU data packet sizes

leads to reducing the data collisions because the other nodes are prohibited from using this channel. Both CR-MAC and DCA-MAC are not using this feature since the whole FCL and not a specific data channel is carried by the RTS control message. Thus, the transmitter's neighbors are not informed about the proposed data channel. Secondly, unlike CR-MAC and DCA-MAC, the response to the appearance of PUs in SWITCH is high. The SWITCH protocol uses the concept of BC as a reaction to the PU's appearance. The BC is negotiated between the transmitter and receiver prior to an actual channel switch. Thus, it minimizes the coordination control overhead occurring at the beginning of utilizing a new channel. On the contrary, both CR-MAC and DCA-MAC are re-establishing the connection in the case of PU's appearance which increases the overhead and therefore decreases the throughput.

Impact of SU data packet size

Here, we show how the data packet size of an SU affects the performance of SWITCH. As mentioned before, SWITCH uses a CCC for exchanging control information and coordinating access to data channels among SUs. Therefore, the unavailability of the CCC affects greatly the SU performance. Figure 4.12 shows the throughput of SUs as a function of PU traffic load. In addition, we show the effect of the data packet size. Three different SU data packet sizes, S_2 are used, 500, 1000 and 1250 Bytes. Furthermore, we set C_1 and C_2 to be equal to 10 and 0 channels respectively.

Interestingly, for large packet size, $S_2 = 1250$ Byte, the network achieves a high throughput, see Figure 4.12. This is because the SUs do not need many new arrangements for long data transmissions. Therefore, the control overhead is reduced and thus the CCC is available and less saturated. We clearly see that when the data packet is small the impact of CCC unavailability is rather high. From this figure, we conclude that the availability of the CCC can be increased by controlling and tuning the SU data packet size. Clearly, increasing the PU traffic load will lead to interrupting the SUs transmission and therefore the transmitter/receiver pair has to make a new arrangement in the CCC and thus reducing the availability of the CCC. This explains why the throughput for the three different data packet sizes decreases with increasing the PU traffic load.

It is intuitively clear that when the SU data packet size increases, the SU packet loss rate increases with increasing PU traffic load. Generally, increasing the packet lose rate affects negatively and greatly the throughput. By utilizing the concept of BC, this effect can be reduced. Figure 4.12 illustrates that starting from point B, where $\rho_1 = 0.38$, the throughput of SU with small data packet size, $S_2 = 500$ outperforms slightly the throughput obtained from other SU packet sizes (i.e.$S_2 = 1000$ and 1250). However, this is a slight enhancement compared to the overall enhancement gained from the throughput of large packet size.

Impact of UCs

Here, we show the impact of UCs in addition to the number of LCs in the performance of SWITCH. Figure 4.13 shows the saturation throughput of the SUs using the SWITCH protocol as a function of the PU traffic load and using both LCs and UCs. In addition, we generate different CU traffic loads in the UCs to investigate the effect of CUs on the SWITCH protocol. To make a fair comparison between SWITCH and DCA-MAC, we use the same number of channels for each protocol. However, each protocol utilizes different types of channels. For DCA-MAC, we set the number of LCs equal to 12 channels since this protocol operates over the LCs only. For the SWITCH protocol, we set the number of LCs equal to 10 channels and the number of UCs equal to 2 channels.

Figure 4.13 illustrates that the performance of the SWITCH protocol outperforms DCA-MAC. Furthermore, it outperforms the performance of the SWITCH protocol that is operated in the LCs only. At low CU traffic load and using both LCs and UCs, SWITCH increases the average throughput compared to the DCA-MAC protocol and the SWITCH protocol using the LCs only. This enhancement is expected since for low CU traffic load, the two UCs are utilized somehow exclusively by the SUs. Thus, when the SU data transmission is interrupted it will continue transmission in the UCs and no interruption is happening anymore. On the contrary, when the PUs appears in DCA-MAC, the SU data transmission is interrupted and a new transmission is established. This process continues till the SU data transmission is completed. This explains the significant improvement on the throughput for the SWITCH protocol compared to DCA-MAC.

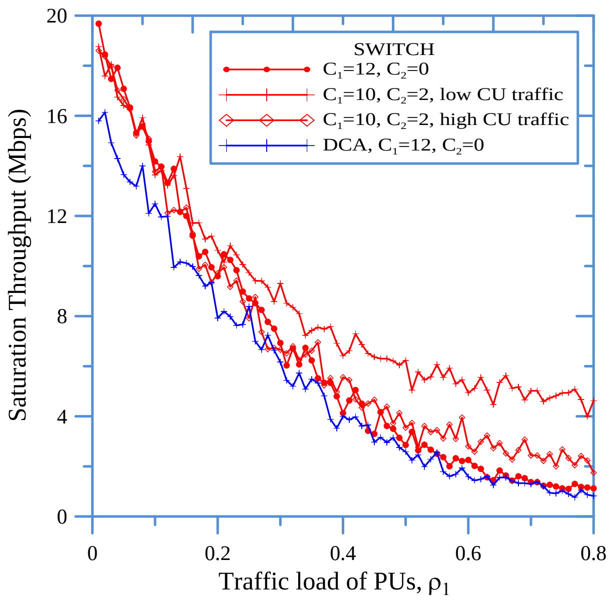


Figure 4.13: Saturation throughput of the SUs as a function of PU traffic load ρ_1 with different number of UCs: For SWITCH, $C_1 = 10$ and $C_2 = 2$ and $\rho_3 = 0.1$ and 0.9. For DCA, $C_1 = 12$ and $C_2 = 0$

For a high traffic load of CUs and using both LCs and UCs, SWITCH increases the throughput compared to DCA-MAC and SWITCH, using the LCs only, by 91.7% and 63.5%, respectively. Interestingly, although DCA-MAC utilizes 12 LCs and SWITCH utilizes only 10 LCs and two highly loaded UCs, SWITCH outperforms DCA-MAC. We can explain that as follows. Even if the two UCs are highly loaded, there is a chance for the SUs to access the UCs since all users in the UCs have the same priority to access the channels. In addition, the concept of BC empowers the SUs with the ability of fast and smooth link maintenance in the case of PU appearance.

Impact of the data rate

Figure 4.14 depicts the impact of changing the data rate in both LCs and UCs. Two different scenarios are implemented to evaluate SWITCH:

- In the first scenario, the data rate for LCs, D_1, and the data rate for UCs, D_2 are set to $1Mbps$. Furthermore, moderate and high traffic loads for CUs are generated on UCs (i.e., $\rho_3 = 0.45$ and $\rho_3 = 0.9$).
- In the second scenario, the data rates for LCs and UCs are $D_1 = 1Mbps$ and $D_2 = 0.5Mbps$, respectively.

Obviously, increasing the data rate for both LCs and UCs leads to increasing the throughput of SUs. However, this increase differs based on CUs activities in the

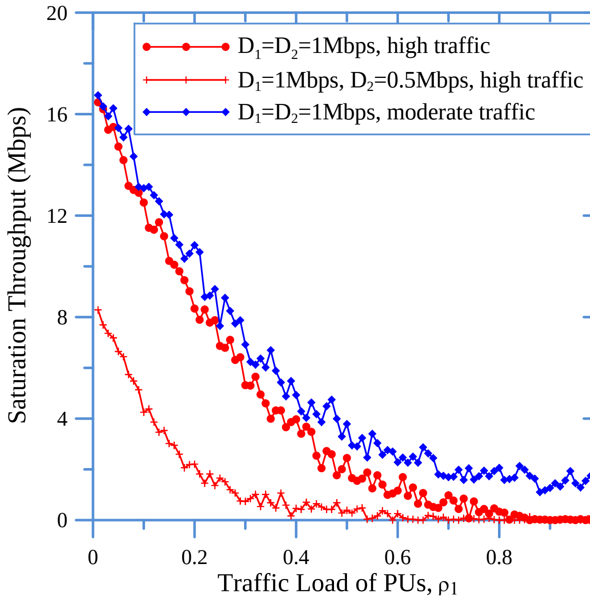


Figure 4.14: Saturation throughput of the SUs in SWITCH as a function of PU traffic load ρ_1 with different data rates: $C_1 = 8$ and $C_2 = 4$

LCs. Clearly, if there is a high CU traffic load on LCs, the throughput will be decreased.

4.5 Chapter summary

The chapter can be summarized as follows:

- SWITCH is a decentralized, asynchronous, and contention-based MAC protocol over a CR ad hoc network. SWITCH is used to implement the OSAB concept presented in Chapter 3. The proposed protocol operates over both LCs and UCs. This feature makes SWITCH a novel MAC protocol compared to the other CR-MAC protocols presented in Chapter 2.

- To detect the availability of unused channels (i.e. LCs or UCs), we have proposed an efficient spectrum sensing strategy. This strategy is based on cooperative spectrum sensing among SUs.

- SWITCH uses the BC concept which has a great impact in establishing faster and smoother link maintenance for the SUs in the case of PUs appearance.

- The proposed data channel and the backup channel are carried by SWITCH control messages. This feature eliminates the need for control messages in the case of PU appearance and therefore reduces the overhead. Upon receiving those control messages, the neighboring nodes will take both channels into consideration when establishing a future communication. Therefore, data collisions are reduced.

- Using simulation, we were able to compare SWITCH with other MAC protocols in a cohesive manner. We draw important conclusions from our study such as:

  1. The negative impact of sudden and consequence PU appearance can be mitigated by using BCs. SWITCH increases the throughput up to 91% compared to other CR-MAC protocols. This is due to the concept of BC which is selected by both the transmitter and the receiver prior to an actual channel switch. Therefore, it minimizes the overhead needed to maintain the SU's link in the case of PU appearance.
  2. A combination of channels from LCs and UCs as a spectrum environment for ad hoc devices is a better approach for efficient utilization of the available spectrum. This fact has been approved by the results obtained from the simulation where the throughput for the SWITCH protocol operating over LCs and UCs outperforms the throughput for the same protocol operating over LCs only. Moreover, we have shown that even if the UCs are saturated by the classical users' traffic, SWITCH increases the throughput compared to other CR-MAC protocols.
  3. The impact of common control channel unavailability can be reduced by transmitting large SU data packet size. This is because the SUs do not need many new arrangements for long data transmissions. Therefore, the control overhead is reduced and thus the control channel is available and less saturated.

Chapter 5

Summary, Conclusion and Future Work

There is no doubt that the growing proliferation of wireless ad hoc devices in the unlicensed bands (e.g. ISM bands) will lead to an increase in data collisions and therefore affects the performance of ad hoc networks negatively. Thus, new spectrum access concepts are needed to reuse the unused licensed spectrum in order to increase the capacity of such networks. The OSA concept is a step towards solving the spectrum inefficiency problem in todays ad hoc networks. CR is a promising technology to realize OSA. Based on OSA and CR, ad hoc devices can reuse the spectrum that is not utilized by licensed devices. Therefore, the spectrum capacity for ad hoc networks will be increased. To profit from the advantages of such future spectrum management approaches, several challenges, such as spectrum sensing, spectrum access (MAC protocols) and spectrum mobility, have to be solved. Spectrum sensing has been evaluated extensively in the last few years. Despite their importance, MAC protocols and spectrum mobility are less explored. Thus, the main contribution of this thesis is developing solutions to overcome the two aforementioned challenges.

5.1 Summary of contributions

This thesis has been structured by means of two major contributions; whereas the two contributions depend on each other. The contributions are:

1. Chapter 3 presents a new spectrum management concept that organizes the access to the available spectrum regardless of the fact that the spectrum is licensed or unlicensed. This concept is named Opportunistic Spectrum Access with Backup Channels (OSAB);

2. Chapter 4 introduces a flexible CR-MAC protocol to benefit from the advantages of the new spectrum concept. This protocol is named Opportunis-

tic Spectrum Access WITh Backup CHannel MAC (SWITCH),

Now, we will show the most important conclusions derived from those two contributions. Most important conclusions are given in the boxes.

5.1.1 OSAB: A new spectrum access concept

One of the most remarkable observations that we got from our extensive survey in Chapter 2 was:

> *The spectrum scarcity problem is a result of the way the spectrum is regulated, and is not due to limited radio resources. Thus the traditional regulation of spectrum requires a fundamental rethinking in order to avoid waste of spectrum. However, this is very difficult and takes a long time for regulators.*

Therefore, a new spectrum management concept is a must to improve the performance of future ad hoc networks without changing the spectrum regulation. OSA is a powerful candidate to achieve that. However, OSA is not organizing and managing the access to the available resources efficiently. In addition, OSA is not reacting to the appearance of PUs quickly. Thus, we have introduced a new spectrum management concept, called OSAB, in Chapter 3. OSAB has been developed to overcome the two aforementioned problems. OSAB is a modified version of OSA that utilizes the network resources, in terms of channels (LCs or UCs), efficiently.

> *The OSAB concept is a step towards eliminating the spectrum scarcity in today's ad hoc networks. It increases the spectrum capacity for ad hoc networks and in addition it reduces the impact of the consecutive spectrum handoffs of SUs.*

Ad hoc networks based on the OSAB concept will operate over two types of channels (LCs and UCs) instead of operating over one type of channels like classical ad hoc networks. Since each type has its own advantage, a combination of LCs and UCs as a spectrum environment for future ad hoc networks is a better approach for benefiting from both types of channels rather than using LCs only. A comprehensive analytical model based on Markov chain has been developed to evaluate extensively the performance of SUs in OSAB in terms of six different performance metrics such as the blocking probability, dropping probability, throughput, successful transmission probability, the expected number of spectrum handoffs and effective transmission time. Numerical results obtained from the Markov chains model have shown that.

> *The dropping and blocking probabilities for the OSAB network is decreased compared to OSA networks. The reason is the combination of channels that OSAB networks operate on. This combination gives SUs the opportunity to reduce the impact of the PU's appearance.*

Furthermore, since the OSAB concept uses the available network resources efficiently, it increases the throughput for the SUs compared to OSA. To make a fair comparison with OSA, we took into consideration the traffic load of the CUs in the UCs.

> *For moderate and high CU traffic loads, OSAB has increased the SU throughput compared to OSA by 95.4% and 76.59%, respectively.*

This is due to the fact that OSAB is not neglecting the existence of the UCs. Furthermore, as a result of utilizing the UCs as BCs, the expected number of spectrum handoffs and the effective transmission time for SU were also reduced.

> *Compared to OSA, OSAB has reduced the SU effective transmission time by 30.3% and 26.5% for moderate and high CU traffic load, respectively.*

Since the OSAB concept takes into consideration the existence of different users such as PUs, SUs and CUs, it provides somehow a load balancing for all users to access the available spectrum.

5.1.2 SWITCH MAC protocol

In the second contribution, we have designed a MAC protocol to implement the OSAB concept. The new protocol was named SWITCH. In our proposed protocol, each SU is equipped with two transceivers. One transceiver is tuned to the common control channel, while the other is designed specifically as a cognitive radio that can periodically sense and dynamically use the identified unused channels (i.e., LCs and UCs). To obtain the channel state accurately, we have proposed an efficient spectrum sensing strategy. This strategy is based on cooperative spectrum sensing among SUs to help SWITCH to detect the availability of leftover channels. The SWITCH protocol is flexible to operate over the LCs and the UCs. According to this feature

> *The SWITCH protocol is different from other CR-MAC protocols in the way that it accesses the available spectrum. It utilizes LCs as operating channels and UCs as backup channels in case of a PU's appearance. On the contrary, other CR-MAC protocols utilize LCs, only.*

Although the way the SUs cope with the sudden appearance of PUs is one of the most important design features for CR-MAC protocols, most of these protocols are not reacting efficiently to such appearance. The SWITCH protocol, developed in this thesis, reacts efficiently to the appearance of PUs by using the BC conception. The BC is negotiated between the transmitter and receiver prior to the actual data transmission. According to this feature:

> *The SWITCH protocol minimizes the overhead needed to maintain the SU's link in the case of PU appearance.*

An extensive simulation has been developed to measure the performance of the SWITCH protocol. The results show that:

> *SWITCH increases the throughput for SUs compared to DCA-MAC by 91.7%. This is due to the concept of BC which is selected by both the transmitter and receiver prior to an actual channel switch.*

Since SWITCH utilizes the CCC for exchanging control packets and coordinating access to data channels, the availability of the CCC greatly affects the SU performance. The availability of the CCC can be enhanced by controlling the SU data packet size.

> *The larger the SU data packet size, the higher the availability of the CCC. This leads to increasing the overall throughput for the SUs.*

In the light of the results presented above, we can strongly say that the flexibility to access the available spectrum regardless of the fact that it is licensed or unlicensed, the efficient spectrum utilization and a fast link maintenance, are the key components to increase the spectrum capacity and to manage the access to the available spectrum efficiently for future ad hoc networks. However, we strongly feel that the obtained results here are just a small fraction of the results that can be gained from using the OSAB concept.

5.2 Future research directions

Although OSAB is an efficient spectrum management concept compared to OSA, we do not claim that OSAB has solved all the problems associated with spectrum allocation in CR ad hoc networks. There exist several open research challenges that need to be investigated for more efficient access to the available spectrum. One of these challenges is utilizing a distributed radio environment map. This map is a database that consists of multi-domain environmental information and prior knowledge, such as the available networks and services, spectral regulations, locations and activities of primary users, primary users' policies and service providers. Thus, this map can be distributed among CR users to obtain a large picture about most or all radio resources in their vicinity. Based on the collected information cognitive engine employed by each CR users can make an accurate decision in the case of primary users' appearance. To the best of our knowledge, the implementation of such radio environment map coupled with a powerful decision making algorithm in the context of CR ad hoc network, is not investigated till now. Work is in progress for building a prototype for CR ad hoc networks. This prototype will enable us to investigate different challenges related to CR ad hoc networks. In addition, the prototype will give us the ability to implement the SWITCH protocol and compare its operation with the simulation results obtained in this thesis.

Appendix A

Mathematical derivation

In this appendix, we derive the mathematical formulas for spectrum handoffs probability obtained in Chapter 3.

Calculating P_k^{UC}: The value of the $\Pr\left[P_k^{UC}\right]$ can be obtained as follows.

$$
\begin{aligned}
& \Pr\left[P_k^{UC}\right] \\
= & \sum_{j=0}^{\infty} \Pr\left[T_s > \Phi_{k+j}\right] \begin{pmatrix} k+j-1 \\ j \end{pmatrix} L_{LC}^{k-1} P_{NH}^{j} L_{UC} \\
= & \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{\Phi_{k+j}}(t) \Pr\left[T_s > t\right] \begin{pmatrix} k+j-1 \\ j \end{pmatrix} (L_{LC})^{k-1} P_{NH}^{j} L_{UC} \\
= & \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{\Phi_{k+j}}(t) \left(1 - \Pr\left[T_s < t\right]\right) \begin{pmatrix} k+j-1 \\ j \end{pmatrix} (L_{LC})^{k-1} P_{NH}^{j} L_{UC} \\
= & \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{\Phi_{k+j}}(t) \left(1 - F_{T_s}(t)\right) \begin{pmatrix} k+j-1 \\ j \end{pmatrix} (L_{LC})^{k-1} P_{NH}^{j} L_{UC} \\
= & \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{\Phi_{k+j}}(t) \overline{F_{T_s}}(t)\, dt \frac{(k+j-1)!}{j!k-1!} (L_{LC})^{k-1} P_{NH}^{j} L_{UC}
\end{aligned}
\tag{A.1}
$$

Substituting the value $f_{\Phi_k}(t) = \frac{\lambda_1 (\lambda_1 t)^{k-1}}{(k-1)!} e^{-\lambda_1 t}$ in A.1, we obtain

$$
\begin{aligned}
& \Pr\left[P_k^{UC}\right] \\
= & \sum_{j=0}^{\infty} \int_{t=0}^{\infty} \frac{\lambda_1 (\lambda_1 t)^{k+j-1}}{(k+j-1)!} e^{-\lambda_1 t} \overline{F_{T_s}}(t)\, dt \frac{(k+j-1)!}{j!k-1!} (L_{LC})^{k-1} P_{NH}^{j} L_{UC} \\
= & \frac{\lambda_1^k (L_{LC})^{k-1} L_{UC}}{(k-1)!} \int_{t=0}^{\infty} t^{k-1} e^{-\lambda_1 t} \overline{F_{T_s}}(t)\, dt \sum_{j=0}^{\infty} \frac{(\lambda_1 t P_{NH})^j}{j!}
\end{aligned}
$$

$$\begin{aligned}
&= \frac{\lambda_1^k \left(L_{LC}\right)^{k-1} L_{UC}}{(k-1)!} \int_{t=0}^{\infty} t^{k-1} \overline{F_{T_s}}(t)\, dt \times e^{-\lambda_1 t} e^{-\lambda_1 P_{NH} t} \\
&= \frac{\left(\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_{UC}}{(k-1)!} \int_{t=0}^{\infty} t^{k-1} e^{-\lambda_1 (1-P_{NH}) t} \overline{F_{T_s}}(t)\, dt \\
&= \frac{\left(\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_{UC}}{(k-1)!} \frac{d^{k-1}}{d^{k-1}\left(\lambda_1 \left(1-P_{NH}\right)\right)} \left[\int_{t=0}^{\infty} e^{-\lambda_1 (1-P_{NH}) t} \overline{F_{T_s}}(t)\, dt\right] \\
&= \frac{\left(\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_{UC}}{(k-1)!} \frac{d^{k-1}}{d^{k-1}\left(\lambda_1 \left(1-P_{NH}\right)\right)} \left[\overline{F}^{*}_{T_s}\left(\lambda_1 \left(1-P_{NH}\right)\right)\right] \\
&= \frac{\left(-\lambda_1 L_{LC}\right)^{k-1} \lambda_1 L_{UC}}{(k-1)!} \overline{F}^{*(k-1)}_{T_s}\left(\lambda_1 \left(1-P_{NH}\right)\right) \qquad \text{(A.2)}
\end{aligned}$$

where $\overline{F}^{*(k-1)}_{T_s}$ denotes the derivative of $(k-1)$th order.

Calculating P_k^{LC}: The value of the $\Pr\left[P_k^{LC}\right]$ can be obtained as follows.

$$\begin{aligned}
&\Pr\left[P_k^{LC}\right] \\
&= \sum_{j=0}^{\infty} \Pr\left[\Phi_{k+j} < T_s < \Phi_{k+j+1}\right] \binom{k+j}{j} L_{LC}^k P_{NH}^j \\
&= \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \Pr\left[\Phi_{k+j} < t < \Phi_{k+j+1}\right] \binom{k+j}{j} L_{LC}^k P_{NH}^j \\
&= \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \int_{x=0}^{t} f_{\Phi_{k+j}}(x) \int_{y=t-x}^{\infty} f_{\Phi_1}(y)\, dy dx dt \frac{(k+j)!}{j!k!} L_{LC}^k P_{NH}^j \\
&= \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \int_{x=0}^{t} f_{\Phi_{k+j}}(x) \int_{y=t-x}^{\infty} \lambda_1 e^{-\lambda_1 y} dy dx dt \frac{(k+j)!}{j!k!} L_{LC}^k P_{NH}^j \\
&= \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \int_{x=0}^{t} \frac{\lambda_1 \left(\lambda_1 x\right)^{k+j}}{(k+j)!} e^{-\lambda_1 x} e^{-\lambda_1 (t-x)} dx dt \frac{(k+j)!}{j!k!} L_{LC}^k P_{NH}^j \\
&= \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \int_{x=0}^{t} \frac{\lambda_1 \left(\lambda_1 x\right)^{k+j}}{k!} e^{-\lambda_1 t} dx dt \frac{1}{j!} L_{LC}^k P_{NH}^j \\
&= \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \frac{\lambda_1^{k+j} e^{-\lambda_1 t}}{k!} \int_{x=0}^{t} x^{k+j-1} dx dt \frac{L_{LC}^k P_{NH}^j}{j!} \\
&= \frac{L_{LC}^k}{k!} \sum_{j=0}^{\infty} \int_{t=0}^{\infty} f_{T_s}(t) \lambda_1^{k+j} e^{-\lambda_1 t} t^{k+j} dt \frac{P_{NH}^j}{j!} \\
&= \frac{\left(\lambda_1 L_{LC}\right)^k}{k!} \int_{t=0}^{\infty} f_{T_s}(t) t^k e^{-\lambda_1 t} dt \sum_{j=0}^{\infty} \frac{\left(\lambda_1 P_{NH} t\right)^j}{j!} \qquad \text{(A.3)} \\
&= \frac{\left(\lambda_1 L_{LC}\right)^k}{k!} \int_{t=0}^{\infty} f_{T_s}(t) t^k e^{-\lambda_1 t} dt^k e^{\lambda_1 P_{NH} t} \qquad \text{(A.4)}
\end{aligned}$$

$$= \frac{(\lambda_1 L_{LC})^k}{k!} \int_{t=0}^{\infty} f_{T_s}(t)\, t^k e^{-\lambda_1(1-P_{NH})t} dt$$

$$= \frac{(-\lambda_1 L_{LC})^k}{k!} f_{T_s}^{*(k)}(\lambda_1 (1 - P_{NH})) \qquad \text{(A.5)}$$

Calculating P_k^T: The value of the $\Pr\left[P_k^T\right]$ can be obtained as same as $\Pr\left[P_k^{UC}\right]$ and $\Pr\left[P_k^{LC}\right]$

Bibliography

[1] S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, Eds., *Mobile Ad Hoc Networking*. Wiley, 2004.

[2] M. Ilyas, Ed., *The Handbook of Ad hoc Wireless Networks*, 1st ed. CRC Press, 2002.

[3] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, “Crahns: Cognitive radio ad hoc networks,” *Ad Hoc Networks Journal*, vol. 7, no. 5, pp. 810–836, July 2009.

[4] “Report of the spectrum efficiency working group,” Federal Communications Commission, Tech. Rep., November 2002.

[5] Darpa: The next generation (xg) program. [Online]. Available: http://www.darpa.mil/ato/programs/xg/index.htm

[6] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” *IEEE Journal On Selected Areas In Communications*, vol. 23, no. 2, pp. 201–220, February 2005.

[7] B. A. Fette, *Cognitive Radio Technology*, 2nd ed. Academic Press, 2009.

[8] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey,” *Computer Networks Journal (Elsevier)*, vol. 50, no. 13, pp. 2127–2159, September 2006.

[9] M. M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, “Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum,” in *Proc. of the 6th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2005)*, Taormina, Giardini Naxos, 13-16 June 2005, pp. 78–85.

[10] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, “Ieee 802.22: The first cognitive radio wireless regional area network

standard," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 130 –138, January 2009.

[11] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access: Signal processing, networking, and regulatory policy," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79–89, May 2007.

[12] L. Berlemann and S. Mangold, *Cognitive Radio and Dynamic Spectrum Access*, 1st ed. John Wiley, 2009.

[13] P. Mohapatra and S. V. Krishnamurthy, Eds., *Ad Hoc Networks: Technologies and Protocols*, 1st ed. Springer, 2005.

[14] Itu page on definitions of ism bands. [Online]. Available: http://www.itu.int/ITU-R/terrestrial/faq/index.html

[15] "Reports of commissions rules to permit unlicensed national information infrastructure (u-nii) devices in the 5 ghz band," FCC, Tech. Rep., November 2003.

[16] *ANSI/IEEE Std 802.11-1999 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Std., 1999.

[17] R. Jurdak, C. V. Lopes, and P. Baldi, "A survey, classification and comparative analysis of medium access control protocols for ad hoc networks," *IEEE Communications Surveys*, vol. 6, no. 1, pp. 2–16, First Quarter 2004.

[18] H. Al-Mahdi, M. A. Kalil, F. Liers, and A. Mitschel-Thiel, "Collision reduction mechanism for masked node problem in ad hoc networks," *International Journal of Electronics and Communications*, vol. 63, no. 9, pp. 754–761, September 2009.

[19] L. Kleinrock and F. Tobagi, "Packet switching in radio channels: Part i-carrier sense multiple access and their throughput-delay characteristics," *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1400–1416, December 1975.

[20] P. Karn, "Maca: a new channel access method for packet radio," in *Proc. of the ARRL 9th Computer Networking Conference*, Canada, 22 September 1990, pp. 134–140.

[21] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "Macaw: A media access protocol for wireless lans," in *Proc. of the ACM SIGCOMM Conference*, London, UK, September 1994, pp. 212–225.

[22] S. Ray, J. Carruthers, and D. Starobinski, "Evaluation of the masked node problem in ad hoc wireless lans," *IEEE Transactions on Mobile Computing*, vol. 4, no. 5, pp. 430–442, September 2005.

[23] J. Mo, H.-S. So, and J. Walrand, "Comparison of multi-channel mac protocols," *IEEE Transactions on Mobile Computing*, vol. 7, no. 1, pp. 50–65, Janaury 2008.

[24] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu, "A new multi-channel mac protocol with on-demand channel assignment for mobile ad hoc networks," in *Proc. of the 5th International Symposium on Parallel Architectures, Algorithms, and Networks (ISPAN 2000)*, Dallas, USA, December 2000, pp. 232–236.

[25] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, and J.-P. Sheu, "A multi-channel mac protocol with power control for multi-hop mobile ad hoc networks," *The Computer Journal*, vol. 45, no. 1, pp. 101–110, 2002.

[26] A. Tzamaloukas and J. Garcia-Luna-Aceves, "Channel-hopping multiple access," in *Proc. of the IEEE International Conference on Communications (ICC 2000)*, Louisiana, USA, June 2000, pp. 415–419.

[27] J. So and N. Vaidya, "Multi-channel mac for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *Proc. ACM MobiHoc*, Tokyo, Japan, 24-26 May 2004, pp. 222–233.

[28] J. Chen, S. Sheu, and C. Yang, "A new multichannel access protocol for ieee 802.11 ad hoc wireless lans," in *Proc. of the 14th IEEE International Symposium on Personal, Indoor and Mobile Radio Comm. (PIMRC 2003)*, Beijing, China, September 2003, pp. 2291–2296.

[29] P. Bahl, R. Chandra, and J. Dunagan, "Ssch: Slotted seeded channel hopping for capacity improvement in ieee 802.11 ad hoc wireless networks," in *Proc. of the ACM MobiCom*, Pennsylvania, USA, September 2004, pp. 216–230.

[30] H. So, J. Walrand, and J. Mo, "Mcmac: A multi-channel mac proposal for ad hoc wireless networks," in *Proc. of the IEEE Wireless Comm. and Networking Conference (WCNC 2007)*, Hong Kong, 11-15 March 2007.

[31] *IEEE Standard Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management*, IEEE Std 1900.1-2008 Std., September 2008.

[32] K. C. Chen and R. Prasad, *Cognitive Radio Networks.* Wiley, April 2009.

[33] D. Hatfield and P. Weiser, "Property rights in spectrum: Taking the next step," in *Proc. 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Maryland, USA, 8-11 November 2005, pp. 43–55.

[34] L. Xu, R. Tonjes, T. Paila, W. Hansmann, M. Frank, and M. Albrecht, "Driveing to the internet: Dynamic radio for ip services in vehicular environments," in *Proc. of the 25th Annual IEEE Conference on Local Computer Network (LCN)*, Florida, USA, 8-10 November 2000, pp. 281–289.

[35] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in *Proc. of the IEEE International Mobile Multimedia Communications Workshop (MoMuC 1999)*, San Diego, USA, 15-17 November 1999, pp. 3–10.

[36] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, August 1999.

[37] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," Ph.D. dissertation, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.

[38] J. Jia, Q. Zhang, and X. Shen, "Hc-mac: A hardware-constrained cognitive mac for efficient spectrum management," *IEEE Journal On Selected Areas In Communications*, vol. 26, no. 1, pp. 106–117, January 2008.

[39] P. Pawelczak, R. Venkatesha Prasad, L. Xia, and I. Niemegeers, "Cognitive radio emergency networks - requirements and design," in *Proc. of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Maryland, USA, November 2005, pp. 601–606.

[40] C. Cordeiro and K. Challapali, "C-mac: A cognitive mac protocol for multichannel wireless networks," in *Proc. of the 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007)*, Dublin, Ireland, April 2007, pp. 147–157.

[41] L. Le and E. Hossain, "Osa-mac: A mac protocol for opportunistic spectrum access in cognitive radio networks," in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC 2008)*, Las Vegas, USA, April 2008, pp. 1426–1430.

[42] B. Hamdaoui and K. G. Shin, "Os-mac: An efficient mac protocol for spectrum-agile wireless networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 8, pp. 915–930, August 2008.

[43] Y. R. Kondareddy and P. Agrawal, "Synchronized mac protocol for multihop cognitive radio networks," in *Proc. of the IEEE International Conference on Communications (ICC 2008)*, Beijing, China, 19-23 May 2008, pp. 3198–3202.

[44] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for enhancement of spectrum efficiency," *IEEE Communications Magazine*, vol. 42, no. 3, pp. S8–14, March 2004.

[45] A. Mishra, "A multi-channel mac for opportunistic spectrum sharing in cognitive networks," in *Proc. of the Military Communications Conference (MILCOM 2006)*, Washington D.C., USA, October 2006, pp. 1–6.

[46] L. Ma, C.-C. Shen, and B. Ryu, "Single-radio adaptive channel algorithm for spectrum agile wireless ad hoc networks," in *Proc. of the 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007)*, Dublin, Ireland, 17-20 April 2007, pp. 547–558.

[47] H. Su and X. Zhang, "Cross-layer based opportunistic mac protocols for qos provisionings over cognitive radio wireless networks," *IEEE Journal On Selected Areas In Communications*, vol. 26, no. 1, pp. 118–129, January 2008.

[48] L. Ma, X. Han, and C. C. Shen, "Dynamic open spectrum sharing mac protocol for wireless ad hoc networks," in *Proc. of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Maryland, USA, 8-11 November 2005, pp. 203–213.

[49] I. Joe and S. Son, "Dynamic spectrum allocation mac protocol based on cognitive radio for qos support," in *Proc. of the Japan-China Joint Workshop on Frontier of Computer Science and Technology (FCST 2008)*, Nagasaki, Japan, 27–28 December 2008, pp. 24–29.

[50] H. B. Salameh, M. Krunz, and O. Younis, "Mac protocol for opportunistic cognitive radio networks with soft guarantees," *IEEE Transactions on Mobile Computing*, vol. 8, no. 10, pp. 1339–1352, October 2009.

[51] S.-Y. Hung, Y.-C. Cheng, E. H.-K. Wu, and G.-H. Chen, "An opportunistic cognitive mac protocol for coexistence with wlan," in *Proc. of the IEEE International Conference on Communications (ICC 2008)*, Beijing, China, 19-23 May 2008, pp. 4059–4063.

[52] Z. Ma, Z. Cao, and W. Chen, "A fair opportunistic spectrum access (fosa) scheme in distributed cognitive radio networks," in *Proc. of the IEEE International Conference on Communications (ICC 2008)*, Beijing, China, 19-23 May 2008, pp. 4054–4058.

[53] A. V. Adamis, K. N. Maliatsos, and P. Constantinou, "A new mac protocol with control channel auto-discovery for self-deployed cognitive radio networks," in *European Wireless Conference (EW 2007)*, Paris, France, 1-4 April 2007.

[54] L.-C. Wang, A. Chen, and D. S. L. Wei, "A cognitive mac protocol for qos provisioning in overlaying ad hoc networks," in *Proc. of the 4th IEEE Consumer Communications and Networking Conference (CCNC 2007)*, Las Vegas, USA, January 2007, pp. 1139–1143.

[55] L.-C. Wang, C.-W. Wang, Y.-C. Lu, and C.-M. Liu, "A concurrent transmission mac protocol for enhancing throughout and avoiding spectrum sensing in cognitive radio," in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC 2007)*, Hong Kong, March 2007, pp. 121–126.

[56] T. Shu, S. Cui, and M. Krunz, "Medium access control for multi-channel parallel transmission in cognitive radio networks," in *Proc. of the IEEE Global Telecommunications Conference (GLOBECOM 2006)*, California, USA, November 2006, pp. 1–5.

[57] M. Timmers, A. Dejonghe, L. van der Perre, and F. Catthoor, "A distributed multichannel mac protocol for cognitive radio networks with primary user recognition," in *Proc. of the 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2007)*, Florida, USA, August 2007, pp. 216–223.

[58] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive mac for opportunistic spectrum access in ad hoc networks: A pomdp framework," *IEEE Journal On Selected Areas In Communications*, vol. 25, no. 3, pp. 589–600, April 2007.

[59] J. Gambini, O. Simeone, U. Spagnolini, Y. Bar-Ness, and Y. Kim, "Cognitive radio with secondary packet-by-packet vertical handover," in *Proc. of the IEEE International Conference Communications (ICC 2008)*, Beijing, China, 19-23 May 2008, pp. 1050–1054.

[60] H. Kim and K. G. Shin, "Efficient discovery of spectrum opportunities with mac-layer sensing in cognitive radio networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 5, pp. 533–545, May 2008.

[61] W. Hu, D. Willkomm, G. Vlantis, M. Gerla, and A. Wolisz, "Dynamic frequency hopping communities for efficient ieee 802.22 operation," *IEEE Communications Magazine*, vol. 45, no. 5, pp. 80–87, May 2007.

[62] D. Willkomm, J. Gross, and A. Wolisz, "Reliable link maintenance in cognitive radio systems," in *Proc. of the1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Maryland, USA, 8-11 November 2005, pp. 371–378.

[63] Q. Zhao, "Spectrum opportunity and interference constraint in opportunistic spectrum access," in *Proc. of the IEEE International Conference on Acous-*

tics, Speech and Signal Processing (ICASSP 2007), Hawaii, USA, 22 May 2007, pp. 605–608.

[64] C. Santivanez, R. Ramanathan, C. Partridge, R. Krishnan, M. Condell, and S. Polit, "Opportunistic spectrum access: challenges, architecture, protocols," in *Proc. of the 2nd annual international workshop on Wireless Internet (WICON 2006)*, Boston, USA, 2-5 August 2006.

[65] X. Zhu, L. Shen, and T.-S. P. Yum, "Analysis of cognitive radio spectrum access with optimal channel reservation," *IEEE Communications Letters*, vol. 11, no. 4, pp. 304–306, April 2007.

[66] P. K. Tang, Y. H. Chew, L. C. Ong, and M. K. Haldar, "Performance of secondary radios in spectrum sharing with prioritized primary access," in *Proc. of Military Communications Conference (MILCOM 2006)*, Washington, D.C, USA, 23-25 October 2006, pp. 1–7.

[67] Y. Xing, R. Chandramouli, S. Mangold, and S. S. N, "Dynamic spectrum access in open spectrum wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 626–637, March 2006.

[68] C. P. T. Hong, Y. Lee, , and I. Koo, "Spectrum sharing with buffering in cognitive radio networks," in *Proc. of the 2nd International Conference Intelligent Information and Database Systems (ACIIDS 2010)*, Hue City, Vietnam, 24-26 March 2010, pp. 261–270.

[69] H. Al-Mahdi, M. Kalil, F. Liers, and A. Mitschele-Thiel, "Increasing spectrum capacity for ad hoc networks using cognitive radios: An analytical model," *IEEE Communications Letters*, vol. 13, no. 9, pp. 676–678, September 2009.

[70] J. Gambini, O. Simeone, Y. Bar-Ness, U. Spagnolini, and T. Yu, "Packet-wise vertical handover for unlicensed multi-standard spectrum access with cognitive radios," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 5172–5176, December 2008.

[71] C.-W. Wang and L.-C. Wang, "Modeling and analysis for proactive-decision spectrum handoff in cognitive radio networks," in *Proc. of the IEEE International Conference on Communications (ICC 2009)*, Dresden, Germany, 14-18 June 2009, pp. 1–6.

[72] Y. Song and J. Xie, "Proactive spectrum handoff in cognitive radio ad hoc networks based on common hopping coordination," in *Proc. of the INFOCOM IEEE Conference Computer Communications Workshops*, San Diego, USA, 15-19 March 2010, pp. 1–2.

[73] Y. Zhang, "Spectrum handoff in cognitive radio networks: Opportunistic and negotiated situations," in *Proc. of the IEEE International Conference on Communications (ICC 2009)*, Dresden, Germany, 14-18 Junuary 2009, pp. 1–6.

[74] J. Tian and G. Bi, "A new link maintenance and compensation model for cognitive uwb radio systems," in *Proc. of the 6th International Conference on ITS Telecommunications (ITST 2006)*, Chegdu, China, 21-23 June 2006, pp. 254–257.

[75] M. Kalil, F. Liers, T. Volkert, and A. Mitschele-Thiel, "A novel opportunistic spectrum sharing scheme for cognitive radio ad hoc networks," *Electronic Communications of the EASST*, vol. 17, pp. 676–678, 2009.

[76] M. Kalil, H. Al-Mahdi, and A. Mitschele-Thiel, "Analysis of opportunistic spectrum access in cognitive ad hoc networks," in *Proc. of the 16th International Conference on Analytical and Stochastic Modelling Techniques and Applications (ASMTA 2009)*, Madrid, Spain, 9–12 June 2009, pp. 9–12.

[77] W. Ahmed, J. Gao, H. Suraweera, and M. Faulkner, "Comments on "analysis of cognitive radio spectrum access with optimal channel reservation"," *IEEE Transactions on Wireless Communications*, vol. 8, no. 9, pp. 4488–4491, 2009.

[78] J.-M. Chung, C. H. Kim, J.-H. Park, J. Shin, and D. Kim, "Optimal channel allocation for cognitive radios," *Electronics Letters*, vol. 46, no. 11, pp. 802–803, 2010.

[79] M. Kalil, H. Al-Mahdi, and A. Mitschele-Thiel, "Spectrum handoff reduction for cognitive radio ad hoc networks," in *Proc. of the 7th International Symposium on Wireless Communication Systems (ISWCS'10)*, York, UK, September 2010, pp. 1036–1040.

[80] L. Kleinrock, *Queueing Systems: Theory.* Wiley-Interscience, 1975, vol. 1.

[81] P. Cordier, P. Houze, S. B. Jemaa, O. Simon, D. Bourse, D. Grandblaise, K. Moessner, J. Luo, C. Kloeck, K. Tsagkaris, R. Agusti, N. Olaziregi, Z. Boufidis, E. Buracchini, P. Goria, and A. Trogolo, "E2r cognitive pilot channel concept," in *Proc. of the 15th IST Mobile and Wireless Communications Summit*, Myconos, Greece, 4-6 June 2006, pp. 1–4.

[82] T. X. Brown, "An analysis of unlicensed device operation in licensed broadcast service bands," in *Proc. of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005)*, Maryland, USA, November 2005, pp. 11–29.

[83] D. Cabric, S. Mishra, D. Willkomm, R. Brodersen, and A. Wolisz, "A cognitive radio approach for usage of virtual unlicensed spectrum," in *Proc. of the 14th IST Mobile and Wireless Communications Summit*, Dresden, Germany, 19-23 June 2005.

[84] J. Zhao, H. Zheng, and G.-H. Yang, "Spectrum sharing through distributed coordination in dynamic spectrum access networks," *Wireless Communications and Mobile Computing*, vol. 7, no. 9, pp. 1061–1075, May 2007.

[85] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys and Tutorials*, vol. 11, no. 1, pp. 116–130, March 2009.

[86] A. Mitschele-Thiel, *Systems Engineering with SDL: Developing Performance Critical Communication Systems.* Wiely, 2001.

[87] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, March 2000.

[88] S. C. Jha, M. M. Rashid, V. K. Bhargava, and C. Despins, "Omc-mac: An opportunistic multichannel mac for cognitive radio networks," in *Proc. of the IEEE 70th Vehicular Technology Conference Fall (VTC 2009 Fall)*, Alaska, USA, 20-23 September 2009, pp. 1–5.

Erklärung

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Ilmenau, den 10. Februar 2011   Mohamed Abd rabou Ahmed Kalil

Theses

- The Opportunistic Spectrum Access with Backup channel (OSAB) concept, developed in this thesis, is a step forward towards efficient utilization of the available spectrum.
- OSAB is a dynamic spectrum access concept by wireless ad hoc devices that exploits local and instantaneous spectrum availability on both licensed and unlicensed bands in a non-interfering manner and without licensed users (i.e. primary user) negotiation. In addition, backup channel (BC) concept, proposed by OSAB, minimizes the effect of primary users' appearance.
- Since existing radio systems offer very limited flexibility, cognitive radios (CR), which can sense, learn, decide and act to radio environments, are exploited to support such a dynamic concept.
- A comprehensive analytical model is developed to evaluate OSAB and analyze the CR ad hoc networks.
- OSAB increases the spectrum capacity for ad hoc networks and in addition it reduces the impact of the consecutive spectrum handoffs in the case of primary users' appearance.
- An efficient Medium Access Control (MAC) protocol called opportunistic Spectrum access WITh backup CHannel (SWITCH) protocol has been developed to implement OSAB.
- SWITCH is a decentralized, asynchronous, and contention-based MAC protocol.
- SWITCH proposes a simple and efficient cooperative channel sensing strategy among CR ad hoc nodes for obtaining the channels state accurately. This strategy enables all networked nodes to have up-to-date information about spectrum allocations in their neighborhood.
- The BC's concept makes SWITCH extremely robust to the appearance of primary users and thus provides a quick channel switching compared to the state-of-the-art CR-MAC protocols.

Ilmenau, den 10. Februar 2011 Mohamed Abd rabou Ahmed Kalil